U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-255 292

Tropic Classification of Lakes Using LANDSAT-1 (ERTS-1) Multispectral Scanner Data

Environmental Research Lab.

April 1976

BEST SELLERS

FROM
NATIONAL
TECHNICAL
INFORMATION
SERVICE

Comparison of Energy Consumption Between West Germany and the United States
PB-245 652/ PAT 112 p. PC$5.50/MF$3.00

A Comprehensive Policy to Ameliorate Adverse Impacts of Transportation Facilities
PB-247 823/ PAT 138 p. PC$6.00/MF $3.00

A Comprehensive Policy to Ameliorate Adverse Impacts of Transporation Facilities, Appendix
PB-247 824/ PAT 310 p. PC$9.75/MF$3.00

Demand for Coal for Electricity Generation 1975–1984
PB-245 216/ PAT 40 p. PC$4.00/MF$3.00

A National Study of Adolescent Drinking Behavior, Attitudes and Correlates
PB-246 002/ PAT 405 p. PC$11.00/MF $3.00

Energy from Coal: Guidelines for the Preparation of Environmental Impact Statements
PB-242 960/ PAT 258 p. PC$9.00/MF $3 00

Energy Versus the Environment: The Issues
PB-246 382/ PAT 35 p. PC$4.00/MF $3.00

Improving the Dissemination of Scientific and Technical Information: A Practitioner's Guide to Innovation
PB-247 057/ PAT 203 p. PC$7.75/MF $3.00

Investigation and Evaluation of Cracking in Austenitic Stainless Steel Piping of Boiling Water Reactor Plants
PB-246 645/ PAT 123 p. PC$5.50/MF $3.00

Pipeline Industry's Practices Using Plastic Pipe in Gas Pipeline Facilities and the Resulting Safety Factors
PB-247 301 / PAT 436 p. PC$11.75/MF $3.00

NOx Combustion Control Methods and Costs for Stationary Sources. Summary Study.
PB-246 750/ PAT 117 p. PC$5.50/MF$3.00

Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants
PB-248 200/SET/ PAT 2,504 p. 8 Volumes PC$61.00

Report on Sulfur Oxide Control Technology
PB-246 667/ PAT 89 p. PC$5.00/MF$3.00

Research Evaluation of a System of Natural Air Conditioning
PB-243 498/ PAT 364 p. PC$10.50/MF$3.00

Retrofitting a Residence for Solar Heating and Cooling: The Design and Construction of the System
PB-247 482/ PAT 101 p. PC$5.50/MF$3.00

Saudi Arabia Five-Year Plan, 1975–1980
PB-246 572/ PAT 683 p. PC$16.25/MF$3.00

Shotcrete Practice in Underground Construction
PB-248 765/ PAT 501 p. PC$12.75/MF $3.00

Short-Term Coal Forecast, 1975–1980
PB-247 073/ PAT 120 p. PC$5.50/MF$3.00

State Energy Information Systems: A Survey
PB-247 457/ PAT 64 p. PC$4.50/MF$3.00

A Study of Fixed Capital Requirements of the U.S. Business Economy
PB-248 690/ PAT 84 p. PC$5.00/MF $3.00

Sulfates and the Environment—A Review
PB-248 122/ PAT 155 p. PC$6.75/MF $3.00

HOW TO ORDER

When you indicate the method of payment, please note if a purchase order is not accompanied by payment, you will be billed an addition $5.00 *ship and bill* charge. And please include the card expiration date when using American Express.

Normal delivery time takes three to five weeks. It is vital that you order by number or your order will be manually filled, insuring a delay. You can opt for *airmail delivery* for a $2.00 charge per item. Just check the *Airmail Service* box. If you're really pressed for time, call the NTIS Rush Order Service. (703) 557-4700. For a $10.00 charge per item, your order will be airmailed within 48 hours. Or, you can pick up your order in the Washington Information Center & Bookstore or at our Springfield Operations Center within 24 hours for a $6.00 per item charge.

You may also place your order by telephone or TELEX. The order desk number is (703) 557-4650 and the TELEX number is 89-9405.

Whenever a foreign sales price is NOT specified in the listings, all foreign buyers must add the following charges to each order: $2.50 for each paper copy; $1.50 for each microfiche; and $10.00 for each Published Search.

Thank you for your interest in NTIS. We appreciate your order.

METHOD OF PAYMENT
☐ Charge my NTIS deposit account no.________
☐ Purchase order no.________
☐ Check enclosed for $________
☐ Charge to my American Express Card account number
☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐
Card expiration date________
Signature________
☐ Airmail Services requested

NAME________
ADDRESS________
CITY, STATE, ZIP________

Item Number	Quantity		Unit Price*	Total Price
	Paper Copy (PC)	Microfiche (MF)		
			Sub Total	
			Additional Charge	
			Enter Grand Total	

*All Prices Subject to Change
8/76

Clip and mail to:
NTIS
National Technical Information Service
U.S. DEPARTMENT OF COMMERCE
Springfield, Va. 22161
(703) 557-4650 TELEX 89-9405

211043

PB 255 292

EPA-600/3-76-037
April 1976

Ecological Research Series

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into five series. These five broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The five series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies

This report has been assigned to the ECOLOGICAL RESEARCH series. This series describes research on the effects of pollution on humans, plant and animal species, and materials. Problems are assessed for their long- and short-term influences. Investigations include formation, transport, and pathway studies to determine the fate of pollutants and their effects. This work provides the technical basis for setting standards to minimize undesirable changes in living organisms in the aquatic, terrestrial, and atmospheric environments.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/3-76-037	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Trophic Classification of Lakes Using LANDSAT-1 (ERTS-1) Multispectral Scanner Data		5. REPORT DATE April 1976 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) D. H. P. Boland		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Special Studies Branch Corvallis Environmental Research Laboratory Corvallis, Oregon 97330		10. PROGRAM ELEMENT NO. 1BA608 11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency Office of Research and Development Washington, DC 20460		13. TYPE OF REPORT AND PERIOD COVERED Final - 1972-73 14. SPONSORING AGENCY CODE EPA/ORD

15. SUPPLEMENTARY NOTES

Prepared in cooperation with the Jet Propulsion Laboratory, Pasadena, California and the National Aeronautics and Space Administration, Office of Technology and Utilization, Washington, DC.

16. ABSTRACT

This study evaluates the Earth Resources Technology Satellite One (ERTS-1; i.e., LANDSAT-1) multispectral scanner (MSS) as a means of estimating lacustrine trophic state. Numerical classificatory methods are employed to ascertain the trophic character of 100 lakes in Minnesota, Wisconsin, Michigan, and New York. Principal components analysis is used to derive a multivariate trophic state index (PC1) using the trophic indicators chlorophyll a, conductivity, inverse of Secchi depth, total phosphorus, an algal assay yield, and total organic nitrogen. A binary masking technique is used to extract lake-related MSS data from digital tapes (CCTs). MSS color ratio models are developed which give good estimates of Secchi depth and fair estimates of chlorophyll a levels. Trophic state, as defined by lake position on the first principal component axis (PC1), is predicted using MSS color ratio regression models. Each date of LANDSAT-1 coverage has its unique model. An automatic image processing technique is employed to classify a group of Wisconsin lakes. The utility of the LANDSAT-1 MSS is most apparent when the seasonal contrasts between lakes at different points on the trophic scale are at a maximum. Periods of excessive cloud cover, frames with faulty or missing MSS data, and the need for some ground truth, impair, but do not preclude its use in lake monitoring and classification. The use of CCTs in conjunction with digital image processing techniques is essential if the maximum benefits are to be derived from the LANDSAT-1 MSS.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
*Remote sensing, *Lakes, *Multivariate analysis, Artificial satellites, Water quality, Spaceborne photography, Taxonomy PRICES SUBJECT TO CHANGE	ERTS-1, LANDSAT-1, Lake classification, Trophic state index, Multispectral scanner, Eutrophication, Automatic image processing, Minnesota, Wisconsin, New York, MI	08/H, 20/F, 22/B

18. DISTRIBUTION STATEMENT Release Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 263
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE 9.00

EPA Form 2220-1 (9-73)

☆ U.S. GOVERNMENT PRINTING OFFICE: 1976—697-057/82 REGION 10

EPA-600/3-76-037
April 1976

TROPHIC CLASSIFICATION OF LAKES USING LANDSAT-1 (ERTS-1) MULTISPECTRAL SCANNER DATA

By

D. H. P. Boland

Assessment and Criteria Development Division
Corvallis Environmental Research Laboratory
Corvallis, Oregon 97330

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF RESEARCH AND DEVELOPMENT
CORVALLIS ENVIRONMENTAL RESEARCH LABORATORY
CORVALLIS, OREGON 97330

1a

DISCLAIMER

This report has been reviewed by the Corvallis Environmental Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Mention of trade names or commerical products does not constitute endorsement or recommendation for use.

PREFACE

In this report the satellite under scrutiny is referred to as LANDSAT-1, an acronym for Land Satellite One. It was the first space observatory launched under the National Aeronautics and Space Administration's Earth Resources Technology Satellite Program and originally carried the designation Earth Resources Technology Satellite One (ERTS-1). The series name change was accomplished with the launch of ERTS-2 (i.e., LANDSAT-2) in January 1975.

Both LANDSAT-1 and LANDSAT-2 are still operational at this point in time (November 1975). The third satellite of the series, LANDSAT-3, is tentatively scheduled for launch in February 1977. While this report was of necessity limited to LANDSAT-1, the successful launch of LANDSAT-2, the decision to proceed with LANDSAT-3, and the forthcoming Space Shuttle Program will provide many opportunities to further define the role of orbital-level remote sensors in surveying the earth's lacustrine resource.

ABSTRACT

This study evaluates the Earth Resources Technology Satellite One (ERTS-1; i.e., LANDSAT-1) multispectral scanner (MSS) as a means of estimating lacustrine trophic state and the magnitude of two trophic state indicators.

Numerical classificatory methods are employed to ascertain the trophic character of 100 lakes in Minnesota, Wisconsin, Michigan, and New York using the trophic indicators: chlorophyll a, total organic nitrogen, inverse of Secchi disc transparency, conductivity, total phosphorus, and an algal assay yield. A complete linkage clustering algorithm is first used to examine the lakes for natural clusters. The resultant clusters are not readily interpretable in terms of the three classic states of trophy (oligotrophic, mesotrophic, eutrophic). The hyper-dimensional cloud of data points is then reduced in dimensionality through the ordination technique of principal components analysis. A multivariate trophic state index (PC1) is derived from the principal component analysis.

A binary masking technique is used to extract lake-related MSS data from computer-compatible tapes. Data products are in the form of descriptive statistics and photographic concatenations of lake images.

MSS color ratio regression models are developed which are of practical value for estimating lake Secchi disc transparency and chlorophyll a levels for one date of LANDSAT-1 coverage. The trophic state of lakes, as defined by lake position on the first principal component axis (PC1 value), is predicted using MSS color ratio regression models. Each date of LANDSAT-1 coverage has its unique regression models for the prediction of the trophic indicators and the trophic index; the models for different dates vary greatly in their practical applicability.

The mean infrared-one band intensity levels for several "hypereutrophic" lakes exceed their mean red band intensity levels and effectively isolate them from other lakes in three-dimensional MSS color models.

A Bayes Maximum Likelihood Multispectral Classifier is employed to classify a group of Wisconsin lakes using MSS colors in conjunction with the lakes' trophic state index values. The results are depicted in the form of both gray-scale and color-coded photographic concatenations.

The utility of the LANDSAT-1 MSS is most apparent when the seasonal contrasts between lakes at different points on the trophic scale are at a maximum. Periods of excessive cloud cover, frames with faulty or missing MSS data, and the need for some ground truth, impair, but do not preclude its use in lake monitoring and classification. The use of computer-compatible tapes in conjunction with digital image processing techniques is essential if the maximum benefits are to be derived from the LANDSAT-1 MSS in lake-orientated studies.

CONTENTS

Page

Preface iii
Abstract iv
List of Figures viii
List of Tables xii
Acknowledgements xviii

Sections

I CONCLUSIONS 1

II RECOMMENDATIONS 2

III INTRODUCTION 4
- Statement of Purpose 4
- Format of Report 5
- The Earth Resources Technology Satellite 5
  - Orbit Parameters and Earth Coverage 6
  - Instrumentation 8
  - Products 12
  - Lake Monitoring Potential 12
- Description of the Study Area 13
  - Geographic Area 18
  - Climate 18
  - Geology, Soils, and Land Use 18
- Lake Selection Criteria and Location 18
- Ground Truth Collection 23
  - Lake Site Selection 23
  - Lake Sampling Methods 23
  - Analytical Methods 28

IV LAKE CLASSIFICATION 30
- Lakes as Natural Resources 30
- Lake Succession and Eutrophication 31
  - Lake Succession 31
  - The Concept of Eutrophication 33
  - Trophic State and Trophic Indicators 35
- Multivariate Classification of Lakes 37
  - Cluster Analysis 38
    - Objects and Attributes 38
    - Cluster Method 39
    - Results and Discussion 42
  - Principal Components Ordination 44
    - Methodology 47
    - Results and Discussion 48
  - Summary 55

Sections Page

V LANDSAT-1 MSS DATA EXTRACTION TECHNIQUES AND PRODUCTS 57
  MSS Data Extraction Approaches 57
    Photographic Approach 57
    CCT Approach 58
  CCT Data Extraction Techniques 59
    Image Processing System 59
    Data Extraction Techniques 60
  Digital Image Enhancement Techniques 68
    Color Ratio Technique 68
    Linear Contrast Stretching Technique 68

VI LANDSAT-1 MSS TROPHIC INDICATOR RELATIONSHIPS 72
  Optical Properties of Pure and Natural Waters 72
    Peripheral Effects 76
  Relevant Remote Sensing Literature 82
    Relevant LANDSAT-1 Investigations 84
  Trophic Indicator Estimation 85
    Lake Area Estimation 90
    Secchi Disc Transparency Estimation 92
    Chlorophyll _a_ Estimation 93

VII LAKE CLASSIFICATION USING LANDSAT-1 MSS DATA 98
  Trophic State Index Prediction Using MSS Data 98
    PC1-MSS Regression Analyses 99
  Three-Dimensional MSS Color Ratio Models 108
  Lake Classification Using MSS Data in Conjunction with Automatic Data Processing Technique 115

VII GENERAL SUMMARY 123
  Lake Classification Using Ground Truth 124
  MSS Estimation of Lake Area and Selected Trophic State Indicators 125
  MSS Prediction of Lacustrine Trophic State 126
  Extraction Techniques and Products 126
  LANDSAT-1 Coverage and Quality 127

IX REFERENCES 128

X LIST OF ACRONYMS AND SYMBOLS 147

XI APPENDICES 150
  APPENDIX A Trophic Indicator Data for 100 NES-Sampled Lakes 151
  APPENDIX B Sampling Dates for 100 NES-Sampled Lakes 154
  APPENDIX C Morphometry and Hydrology of Study Lakes 156
  APPENDIX D LANDSAT-1 MSS Models, Concatenations, Areal Relationships, and Descriptive Statistics 161

Sections Page

APPENDIX D1 9 August 1972 (1017-16091, 1017-16093) 162
D2 28 August 1972 (1036-16152) 166
D3 11 June 1973 (1323-16100, 1323-16094) 170
D4 17 July 1973 (1359-16091, 1359-16094) 175
D5 14 August 1972 (1022-16373) 181
D6 6 October 1972 (1075-16321) 189
D7 8 October 1972 (1077-16431) 197
D8 28 May 1973 (1309-16325) 204
D9 3 July 1973 (1345-16322) 210
D10 4 July 1973 (1346-16381) 216
D11 19 August 1972 (1027-15233) 222
D12 11 October 1972 (1080-15180) 228
APPENDIX E N x N Squared Euclidian Distance Matrix 233
APPENDIX F Listing of McKeon Cluster Analysis Program 240

LIST OF FIGURES

Figure		Page
1	LANDSAT-1 ground coverage pattern	7
2	Schematic diagram of the LANDSAT-1 MSS scanning arrangement	10
3	Ground scan pattern for a single MSS detector	11
4	Reproduction of an EROS Data Center IR2 print of Frame 1017-16093 (9 August 1972)	14
5	Reproduction of EROS IR1 print of Frame 1017-16093 (9 August 1972)	15
6	Reproduction of EROS RED (MSS Band 5) print of Frame 1017-16093 (9 August 1972)	16
7	Reproduction of EROS GRN (MSS Band 4) print of Frame 1017-16093 (9 August 1972)	17
8	Physical subdivisions	19
9	Geology	20
10	Distribution of principal kinds of soils: Orders, Suborders, and Great Groups	21
11	Major land uses	22
12	Location of the study lakes	27
13	Hypothetical productivity growth-curve of a hydrosere	34
14	N x N S-matrix	41
15	Dendogram of 100 lakes sampled by the National Eutrophication Survey during 1972	43
16	Geometrical interpretation of the principal components for a hypothetical bivariate system	46
17	Three-dimensional principal component ordination of 100 lakes sampled by the National Eutrophication Survey during 1972	56

Figure		Page
18	Left half of MSS Frame 1017-16093 reproduced using IR2 DN values	61
19	An extracted section of LANDSAT-1 MSS Frame 1017-16093	62
20	First-stage MSS Band 4 (GRN) cleanup picture of Lake Koshkonong	64
21	First-stage MSS Band 5 (RED) cleanup picture of Lake Koshkonong	65
22	Four band (GRN, RED, IR1, IR2) concatenation of Lake Koshkonong	66
23	IR2 concatenation of 15 lakes extracted from LANDSAT-1 MSS Frame 1017-16093	67
24	Lake Koshkonong image enhancement using six LANDSAT-1 MSS ratios	69
25	Contrast stretched images of Lake Koshkonong (9 August 1972)	70
26	Contrast stretched images of Lake Koshkonong (28 August 1972)	71
27	Reflectance curve for distilled water	74
28	Reflection characteristics of filtered and unfiltered water samples from two Wisconsin lakes in the area of Madison	75
29	Spectral distribution of solar energy	78
30	Solar zenith and solar elevation relationship	79
31	Percentage reflectance of the air-water interface as a function of the angle of incidence measured from normal direction	80
32	Comparison of the reflectance of chlorophyll-containing plants with the attenuation length of sunlight in distilled water	95
33	Three-dimensional color ratio model for 9 August 1972	110
34	Three-dimensional color ratio model for 11 June 1973	112

Figure Page

35 Three-dimensional color ratio model for 17 July 1973 113

36 Three-dimensional color ratio model for three dates of LANDSAT-1 MSS coverage (9 August 1972, 11 June 1973, 17 July 1973) 114

37 ADP-classified lakes (9 August 1972), using 19 gray-levels, one for each class 120

38 A color-enhanced version of the 19-class classification of the 20 lakes (9 August 1972) 121

D1-1 IR2 concatenation of 5 Wisconsin lakes extracted from Frame 1017-16091 (9 August 1972) 163

D2-1 IR2 concatenation of 6 Wisconsin lakes extracted from Frame 1036-16152 (28 August 1972) 167

D3-1 IR2 concatenation of 12 Wisconsin lakes extracted from Frame 1323-16100 (11 June 1973) 171

D3-2 IR2 concatenation of 11 Wisconsin lakes extracted from Frame 1323-16100 (11 June 1973) 172

D4-1 IR2 concatenation of 15 Wisconsin lakes extracted from Frame 1359-16094 (17 July 1973) 176

D4-2 IR2 concatenation of 4 Wisconsin lakes extracted from Frame 1359-16091 (17 July 1973) 177

D5-1 Three-dimensional MSS color ratio model of 12 Minnesota lakes extracted from Frame 1022-16373 (14 August 1972) 185

D5-2 IR2 concatenation of 12 Minnesota lakes extracted from Frame 1022-16373 (14 August 1972) 186

D6-1 Three-dimensional MSS color ratio model of 15 Minnesota lakes extracted from Frame 1075-16321 (6 October 1972) 192

D6-2 IR2 concatenation of 8 Minnesota lakes extracted from Frame 1075-16321 (6 October 1972) 193

D6-3 IR2 concatenation of 8 Minnesota lakes extracted from Frame 1075-16321 (6 October 1972) 194

Figure		Page
D7-1	Three-dimensional MSS color ratio model of 10 Minnesota lakes extracted from Frame 1077-16431 (8 October 1972)	200
D7-2	IR2 concatenation of 10 Minnesota lakes extracted from Frame 1077-16431 (8 October 1972)	201
D8-1	Three-dimensional MSS color ratio model of 13 Minnesota lakes extracted from Frame 1309-16325 (28 May 1973)	207
D8-2	IR2 concatenation of 13 Minnesota lakes extracted from Frame 1309-16325 (28 May 1973)	208
D9-1	Three-dimensional MSS color ratio model of 14 Minnesota lakes extracted from Frame 1345-16322 (3 July 1973)	213
D9-2	IR2 concatenation of 14 Minnesota lakes extracted from Frame 1345-16322 (3 July 1973)	214
D10-1	Three-dimensional MSS color ratio model of 8 Minnesota lakes extracted from Frame 1346-16381 (4 July 1973)	218
D10-2	IR2 concatenation of 8 Minnesota lakes extracted from Frame 1346-16381 (4 July 1973)	219
D11-1	Three-dimensional MSS color ratio model of 7 New York lakes extracted from Frame 1027-15233 (19 August 1972)	224
D11-2	IR2 concatenation of 7 New York lakes extracted from Frame 1027-15233 (19 August 1972)	225
D12-1	Three-dimensional MSS color ratio model of 5 New York lakes extracted from Frame 1080-15180 (11 October 1972)	229
D12-2	IR2 concatenation of 5 New York lakes extracted from Frame 1080-15180 (11 October 1972)	230

LIST OF TABLES

Table Page

1 LANDSAT-1 orbital parameters 6

2 LANDSAT-1 MSS characteristics 9

3 Study lakes 24

4 Distribution of the world's estimated water supply 32

5 Trophic indicators and their response to increased 36
eutrophication 36

6 Descriptive statistics of 100 lakes 40

7 R-mode correlation matrix of six trophic state indicators 47

8 Normalized eigenvectors and eigenvalues 49

9 Product-moment correlation coefficients of the trophic state indicators and the principal components 50

10 Principal component ordination and mean composite rank ordination of 100 lakes 51

11 Descriptive statistics of Lake Koshkonong MSS data extracted from Frame 1017-16093 CCTs 63

12 Optical properties of pure water 73

13 Indices commonly used to assess eutrophication 83

14 LANDSAT-1 MSS frames 86

15 Dates of LANDSAT-1 coverage 87

16 Areal aspects of 20 NES-sampled lakes extracted from LANDSAT-1 MSS Frames 1017-16091 and 1017-16093 91

17 Correlations between ground truth and LANDSAT-1 MSS data (colors and color ratios) for 20 lakes in Frames 1017-16091 and 1017-16093 92

18 Analysis of variance table of a regression model for the prediction of Secchi disc transparency 94

Table		Page
19	Secchi disc transparency residuals	94
20	Analysis of variance table of a regression model for the prediction of chlorophyll a levels	97
21	Chlorophyll a residuals	97
22	Correlations between LANDSAT-1 MSS data (colors and color ratios) collected on three dates and the trophic status of 20 Wisconsin lakes	99
23	Analysis of variance table of a regression model for the prediction of the trophic status of lakes found in LANDSAT-1 MSS Frames 1017-16091 and 1017-16093 (9 August 1972)	100
24	Trophic state index (PC1) residuals of 20 Wisconsin lakes found in LANDSAT-1 MSS Frames 1017-16091 and 1017-16093 (9 August 1972)	101
25	Analysis of variance table of a regression model for the prediction of the trophic status of 20 Wisconsin lakes found in LANDSAT-1 MSS Frames 1323-16194 and 1323-16100 (11 June 1973)	102
26	Trophic state index (PC1) residuals of 20 Wisconsin lakes found in LANDSAT-1 MSS Frames 1323-16194 and 1323-16100 (11 June 1973)	102
27	Analysis of variance table of a regression model for the prediction of the trophic status of 20 Wisconsin lakes found in LANDSAT-1 MSS Frames 1359-16091 and 1359-16094 (17 July 1973)	103
28	Trophic state index (PC1) residuals of 20 Wisconsin lakes found in LANDSAT-1 MSS Frames 1359-16091 and 1359-16094 (17 July 1973)	103
29	Analysis of variance table of a regression model for the prediction of trophic status of 20 Wisconsin lakes using MSS color ratios from three dates (9 August 1972, 11 June 1973, and 17 July 1973)	105

Table		Page
30	Trophic state index (PC1) residuals of 20 Wisconsin lakes from a regression model incorporating mean MSS color ratios from three dates (9 August 1972, 11 June 1973, and 17 July 1973)	105
31	Regression models developed for the estimation of trophic state using LANDSAT-1 MSS data	106
32	Lake trophic state index class assignments for the ADP technique	116
33	ADP results for 9 August 1972 using a 19 class classification	117
D1-1	MSS descriptive statistics for 15 Wisconsin lakes extracted from Frame 1017-16093 (9 August 1972)	164
D1-2	MSS descriptive statistics for 5 Wisconsin lakes extracted from Frame 1017-16091 (9 August 1972)	165
D2-1	Areal aspects of 6 Wisconsin lakes extracted from Frame 1036-16152 (28 August 1972)	168
D2-2	MSS descriptive statistics for 6 Wisconsin lakes extracted from Frame 1036-16152 (28 August 1972)	169
D3-1	Areal aspects of 23 Wisconsin lakes extracted from Frames 1323-16094 and 1323-16100 (11 June 1973)	173
D3-2	MSS descriptive statistics for 23 Wisconsin lakes extracted from Frame 1323-16100 (11 June 1973)	174
D4-1	Areal aspects of 21 Wisconsin lakes extracted from Frames 1359-16091 and 1359-16094 (17 July 1973)	178
D4-2	MSS descriptive statistics for 4 Wisconsin lakes extracted from Frame 1359-16091 (17 July 1973)	179
D4-3	MSS descriptive statistics for 17 Wisconsin lakes extracted from Frame 1359-16094 (17 July 1973)	180
D5-1	Correlations between ground truth and MSS data (colors and color ratios) for 11 Minnesota lakes in Frame 1022-16373 (14 August 1972)	181

Table		Page
D5-2	Analysis of variance table for PC1 regression model for 11 Minnesota lakes in Frame 1022-16373 (14 August 1972)	182
D5-3	PC1 residuals of 11 Minnesota lakes in Frame 1022-16373 (14 August 1972)	182
D5-4	Analysis of variance table of the Secchi disc transparency regression model of 11 Minnesota lakes in Frame 1022-16373 (14 August 1972)	183
D5-5	Secchi disc transparency residuals of 11 Minnesota lakes in Frame 1022-16373 (14 August 1972)	183
D5-6	Areal aspects of 12 Minnesota lakes extracted from Frame 1022-16373 (14 August 1972)	187
D5-7	MSS descriptive statistics for 12 Minnesota lakes extracted from Frame 1022-16373 (14 August 1972)	188
D6-1	Correlations between ground truth and MSS data (color ratios) for 12 Minnesota lakes in Frame 1075-16321 (6 October 1972)	189
D6-2	Analysis of variance table for the PC1 regression model for 12 Minnesota lakes extracted from Frame 1075-16321 (6 October 1972)	190
D6-3	PC1 residuals of 12 Minnesota lakes extracted from Frame 1075-16321 (6 October 1972)	190
D6-4	Areal aspects of 15 Minnesota lakes extracted from Frame 1075-16321 (6 October 1972)	195
D6-5	MSS descriptive statistics for 15 Minnesota lakes extracted from Frame 1075-16321 (6 October 1972)	196
D7-1	Correlations between ground truth and MSS data (color ratios) for 7 Minnesota lakes extracted from Frame 1077-16431 (8 October 1972)	197
D7-2	Analysis of variance table of the PC1 regression model for 7 Minnesota lakes extracted from Frame 1077-16431 (8 October 1972)	198

Table Page

D7-3 PC1 residuals of 7 Minnesota lakes extracted from Frame 1077-16431 (8 October 1972) 198

D7-4 Areal aspects of 10 Minnesota lakes extracted from Frame 1077-16431 (8 October 1972) 202

D7-5 MSS descriptive statistics for 10 Minnesota lakes extracted from Frame 1077-16431 (8 October 1972) 203

D8-1 Correlations between MSS data (colors and color ratios) and PC1 values for 11 Minnesota lakes extracted from Frame 1309-16325 (28 May 1973) 204

D8-2 Analysis of variance table of the PC1 regression model for 11 Minnesota lakes extracted from Frame 1309-16325 (28 May 1973) 205

D8-3 PC1 residuals of 11 Minnesota lakes extracted from Frame 1309-16325 (28 May 1973) 205

D8-4 Descriptive statistics for 13 Minnesota lakes extracted from Frame 1309-16325 (28 May 1973) 206

D8-5 Areal aspects of 13 Minnesota lakes extracted from Frame 1309-16325 (28 May 1973) 209

D9-1 Correlations between MSS data (color ratios) and PC1 values for 12 Minnesota lakes extracted from Frame 1345-16322 (3 July 1973) 210

D9-2 Analysis of variance table of the PC1 regression model for 12 Minnesota lakes extracted from Frame 1345-16322 (3 July 1973) 211

D9-3 PC1 residuals of 12 Minnesota lakes extracted from Frame 1345-16322 (3 July 1973) 211

D9-4 MSS descriptive statistics for 14 Minnesota lakes extracted from Frame 1345-16322 (3 July 1973) 212

D9-5 Areal aspects of 14 Minnesota lakes extracted from Frame 1345-16322 (3 July 1973) 215

D10-1 Correlations between MSS data (colors and color ratios) from the PC1 values for 7 Minnesota lakes extracted from Frame 1346-16381 (4 July 1973) 216

Table		Page
D10-2	Analysis of variance table of the PC1 regression model for 7 Minnesota lakes extracted from Frame 1346-16381 (4 July 1973)	217
D10-3	PC1 residuals of 7 Minnesota lakes extracted from Frame 1346-16381 (4 July 1973)	217
D10-4	Areal aspects of 8 Minnesota lakes extracted from Frame 1346-16381 (4 July 1973)	220
D10-5	MSS descriptive statistics for 8 Minnesota lakes extracted from Frame 1346-16381 (4 July 1973	221
D11-1	Correlations between ground truth and MSS data (colors and color ratios) for 7 New York lakes extracted from Frame 1027-15233 (19 August 1972)	222
D11-2	Analysis of variance table of the PC1 regression model for 7 New York lakes extracted from Frame 1027-15233 (19 August 1972)	223
D11-3	PC1 residuals of 7 New York lakes extracted from Frame 1027-15233 (19 August 1972)	223
D11-4	Areal aspects of 7 New York lakes extracted from Frame 1027-15233 (19 August 1972)	226
D11-5	MSS descriptive statistics for 7 New York lakes extracted from Frame 1027-15233 (19 August 1972)	227
D12-1	Areal aspects of 5 New York lakes extracted from Frame 1080-15180 (11 October 1972)	231
D12-2	MSS descriptive statistics for 5 New York lakes extracted from Frame 1080-15180 (11 October 1972)	232

ACKNOWLEDGEMENTS

The scale and scope of this research effort was made possible through the cooperation of the U.S. Environmental Protection Agency, the National Aeronautics and Space Administration, the Jet Propulsion Laboratory (California Institute of Technology), and Oregon State University.

Sincere thanks are extended to Dr. Jack H. Gakstatter of EPA's National Eutrophication Survey for providing ready access to unpublished lake survey data and the welcomed funding for the project. James M. Omernik focused the author's attention on the gray tone differences among NES-sampled lakes found on LANDSAT-1 MSS photographs and suggested that the differences might relate to variations in water quality. Dr. Norbert A. Jaworski is acknowledged for providing the administrative support so vital to the project's completion. Vernard H. Webb of EPA's Environmental Photographic Interpretation Center (EPIC) ably filled the position of NASA principal investigator and facilitated the procurement of the MSS computer-compatible tapes.

Kenneth V. Byram, Lyle A. Wilson, and William C. Tiffany supplied computer programming assistance. Additional logistic support was provided by: Marvin O. Allum, Albert Katko, Cecillia O. Boland, Clarence A. Callahan, Ralph E. Austin, Karen Randolph, and Betty McCauley. Dr. Leslie P. Seyb, Richard J. Blackwell, and Dr. D. Phillips Larsen are thanked for their review commentaries. The manuscript was typed by Carla R. Juilfs, Beverley P. Bowman, and Donald A. Belshee.

It is a pleasure to acknowledge the crucial assistance provided by Dr. Richard H. Green and the personnel of JPL's Image Processing Laboratory. Richard J. Blackwell's expertise in digital image processing was invaluable; his contribution in uncountable hours of concerned discussion and involvement is far greater than the few explicit citations indicate.

Appreciation is extended to Dr. Robert E. Frenkel, Dr. Robert C. Bard, Dr. J. Granville Jensen, Dr. Larry G. Forslund, Dr. Henry A. Froehlich, and Dr. Donald A. Pierce, faculty members at Oregon State University. Dr. Frenkel served as the author's major advisor. Dr. Pierce offered many valuable suggestions relating to statistical techniques.

The Environmental Remote Sensing Applications Laboratory at Oregon State University is acknowledged for permitting the investigator the use of its microdensitometer and for providing access to its LANDSAT-1 browse film library.

This research effort was supported under NASA Contract Number NAS7-100 to the Jet Propulsion Laboratory and JPL Contract Number EZ-608770. Additional computer time was provided through the Oregon State University Computer Center and the National Eutrophication Survey Program.

SECTION I

CONCLUSIONS

Based on the ground truth and the multispectral scanner frames selected for analysis, the image extraction and enhancement techniques and data reduction methods employed, it is concluded that:

1. The LANDSAT-1 MSS is an effective tool for lake enumeration and for the estimation of lake surface area.

2. Estimates of lake Secchi disc transparency and chlorophyll a levels having practical significance can be achieved through the incorporation of lake MSS color ratios in regression models. Each trophic indicator has a model which is unique to the specific date of LANDSAT-1 coverage.

3. MSS color ratios can be used to estimate lake position on a multivariate trophic scale. However, each date of LANDSAT-1 coverage has its unique model. The models for different dates vary greatly in their predictive capabilities. The standard error of the models tends to decrease as the growing season progresses and the manifestations of eutrophication become more evident.

4. While information relating to lacustrine trophic state can be extracted from LANDSAT-1 MSS imagery, either by visual inspection or through microdensitometry and optical density slicing, the maximum benefits in water-based studies can be derived only through the use of the digital data contained on the computer-compatible tapes in conjunction with automatic image processing techniques.

5. Although LANDSAT-1 provides 18-day repetitive coverage, systematic times-series are difficult, if not impossible, to obtain due to excessive cloud cover on many dates of satellite coverage.

6. The LANDSAT-1 MSS has utility as a supplemental data source in lake survey and monitoring programs. Its value is most apparent in situations involving large lakes and/or large numbers of lakes.

SECTION II

RECOMMENDATIONS

In January 1975, NASA inserted its second Earth Resources Technology Satellite (ERTS-2, i.e., LANDSAT-2) into a sun-synchronous near-polar orbit. The orbital parameters of LANDSAT-2 and its still operational predecessor, LANDSAT-1, have resulted in 9-day repetitive coverage. The tandem combination of satellites has effectively doubled the amount of imagery and digital data available to investigators. The increased coverage should be of great value in lake monitoring and survey programs. Lakes are by their very nature dynamic and the more frequent satellite coverage should increase the accuracy of the trophic state estimates.

NASA has been authorized to launch a third Earth Resources Technology Satellite (ERTS-3, i.e., LANDSAT-3) into orbit; the tentative launch date is February 1977. The instrumentation will include an improved multispectral scanner having greater spatial resolution and capabilities in the thermal region of the spectrum. It is anticipated that the improvements will increase the utility of the satellite-borne sensor as a means of classifying lakes.

As of September 1975, the LANDSAT series of earth resources satellites has amassed an inventory numbering in excess of 150,000 frames (scenes) of the United States. The collection is expanding at an average rate of about 190 frames per day. It is maintained by the EROS Data Center at Sioux Falls, South Dakota.

A magnetic tape library has been established at JPL's Image Processing Laboratory for the lakes examined during the course of this investigation. The lake images have been extracted from their terrestrial matrix and are readily available for additional statistical analyses using automatic digital image processing techniques. The enlargement of this library through continued acquisition of MSS data for NES-sampled lakes will give researchers the opportunity to study long-term changes in the lakes.

In light of the preceding information and the conclusions drawn from this investigation, it is recommended that additional effort be expended to refine the predictive capabilities of the LANDSAT MSS. Several problem areas which merit additional consideration have been identified.

The development of a more representative trophic state index may well be in order. Although automatic data processing techniques (such as cluster analysis) have a role in the classification of lakes, the kinds and number of trophic indicators, the types of data transformations, and the methodologies employed can produce significant differences in the resulting classifications, Very little work has been done in this area using the techniques commonly employed in numerical taxonomy. ADP techniques are well suited for the reduction of the large data masses generated by lake survey programs.

Although atmospheric and solar angle effects were disregarded, it is apparent that they can degrade the lake color signal received by the multispectral scanner. The development of radiometric calibration techniques to account for the peripheral effects would greatly increase the utility of the MSS. An increase in instrument gain (this is possible in the RED and GRN bands) would aid the water-based investigator, possibly at the expense of terrestrial studies.

The need exists to study in greater detail the relationships between the magnitude of trophic state indicators and MSS data under both laboratory and field conditions. This study suffered in part from the lack of concurrent data; it is imperative that concurrent satellite-ground truth sampling be conducted to further elucidate the relationships.

Bottom effects were assumed to be insignificant in this study because Secchi disc transparency was much less than water depth. However, in some lakes the bottom can be seen by the sensor. A better knowledge of bottom effects may be of value in refining the predictive capabilities of the MSS in the aquatic environment.

With the exception of some lakes in the New York frames, the remote sensing aspects of this investigation have been heavily weighted with lakes that are often referred to as "eutrophic". The need exists to examine more lakes, particularly those possessing high water quality. The sensitivity limits of the MSS have yet to be established for trophic state indicators as well as the trophic state index. The examination of lakes from other geographic regions should be undertaken to determine whether the relationships found in the study area extend to other regions.

SECTION III

INTRODUCTION

Homo sapiens has developed the burgeoning population and the technological level necessary to effect significant alterations in the biosphere. His impact on environment is accelerating in variety, magnitude, and geographic extent. He has failed, either through gross ignorance or a lack of concern, to give adequate consideration to the interrelatedness of the biotic and abiotic elements which compose the environment. Man-induced environmental alterations generally result in a chain of consequences, both direct and indirect, short-term and long-term, and varying in magnitude. Many of the consequences (e.g., air pollution, water pollution) adversely affect his health, his economic well-being, and the pristine qualities of environment.

Man's strategies for using the earth's lacustrine resources have usually been predicated on immediate short-term economic gains with little consideration of long range environmental ramifications. It is becoming increasingly apparent that man has adversely affected many lakes, particularly those located in countries with large population densities and/or which are technologically advanced. The United States of America can serve as a prime example.

STATEMENT OF PURPOSE

Rational management of the lacustrine resource dictates, as the first step, an assessment of each lentic body's trophic status. Data collection for the determination of trophic status is a costly, time-consuming process, especially when thousands of lakes are to be evaluated. The need exists to find a means of rapidly assessing the trophic state of water bodies which would make it economically feasible to operate extensive systematic surveillance programs. Stewart and Rohlich (1967) have urged investigators to develop remote sensing techniques and evaluate their potential for eutrophication surveillance.

Satellite-borne sensors show promise as a means of monitoring and classifying lakes and reservoirs. The successful orbiting of the Earth Resources Techology Satellite (ERTS-1; i.e., LANDSAT-1) affords the opportunity to investigate the potential of one type of satellite-borne sensor.

The purpose of this report is the evaluation of LANDSAT-1 remotely sensed multispectral scanner data as a means of determining the trophic state of a selected group of lakes located in the northern part of the conterminous United States. Specific objectives include: the development and application of a multivariate trophic ranking system to a selected group of lakes; the formulation of empirical models for the estimation of selected trophic state indicators; and the development of empirical models for the prediction of lacustrine trophic state using LANDSAT-1 data.

FORMAT OF REPORT

The remainder of this section is devoted to a description of the Earth Resources Technology Satellite, its orbital characteristics, instrumentation, and products. In addition, the study area is described along with the criteria used in the selection of the lakes and the techniques used in the collection of the ground (i.e., water) truth.

Section IV discusses lakes as natural resources, the concept of eutrophication, trophic state indicators, and demonstrates the use of multivariate techniques in the classification of a large group of lakes on the basis of selected ground truth parameters.

Section V is devoted to a detailed description of the methodology used in the extraction and transformation of LANDSAT-1 multispectral scanner (MSS) data into forms and products which can then be used in the study of hypothesized ground truth-MSS data relationships.

Correlations between lake parameters (surface area, chlorophyll a, Secchi disc transparency) and MSS data are explored in Section VI. Regression models are developed to predict the magnitude of selected trophic state indicators.

Section VII includes the prediction of lake trophic state using MSS color ratios in regression models. Three-dimensional models are used to illustrate qualitative differences among the lakes on the basis of MSS color ratios. An automatic image processing technique is employed to generate enhanced photographic products depicting the trophic state of selected lakes.

Section VIII is devoted to a brief discussion and summation of the potential applications and limitations of the LANDSAT-1 MSS in lake monitoring and classification.

THE EARTH RESOURCES TECHNOLOGY SATELLITE

The Earth Resources Technology Satellite Program, under the sponsorship of the National Aeronautics and Space Administration, is a concerted effort to merge space and remote sensing technologies into a system which will demonstrate techniques for efficient management of the earth's natural resources. To explore the feasibility of applying earth resource data collected from satellite altitudes to resource management problems, NASA inserted an experimental satellite (ERTS-A) into a circular earth orbit. Another satellite (ERTS-B) is scheduled for launch when ERTS-A, officially designated ERTS-1 (i.e., LANDSAT-1) ceases to function. Detailed information regarding the Earth Resources Technology Program is found in the Data Users Handbook (NASA, 1972).

ERTS-1 Orbit Parameters and Earth Coverage

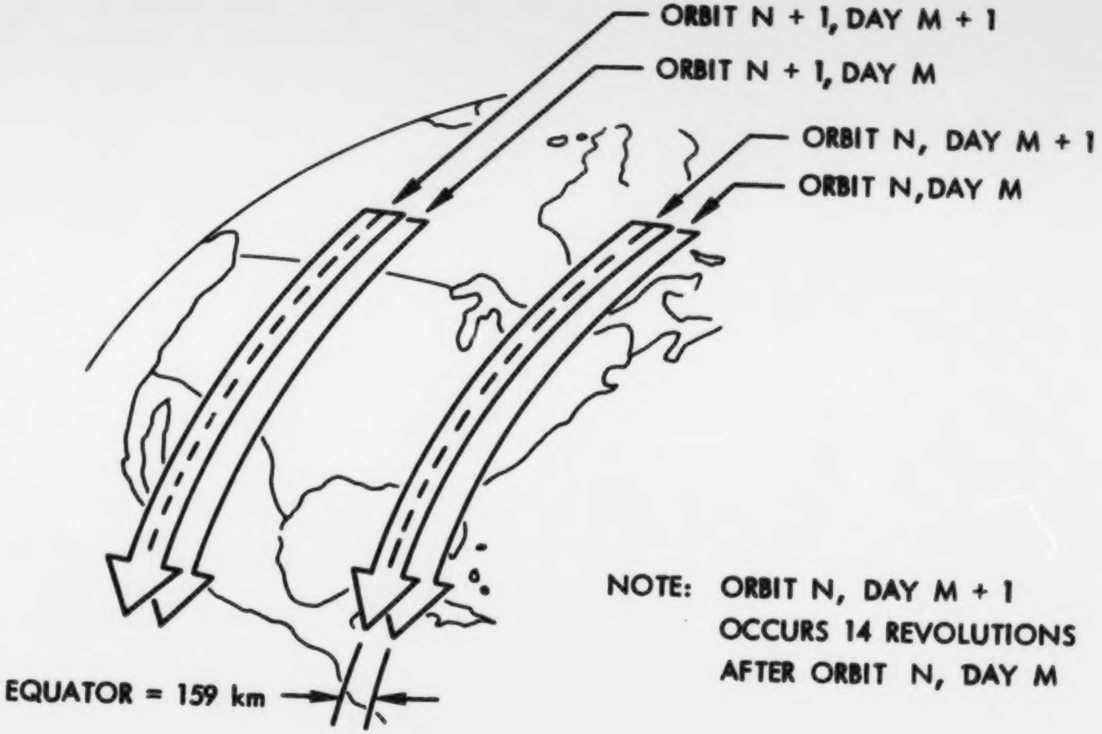
LANDSAT-1 was placed into a nominal sun-synchronous near-polar orbit by a Delta launch vehicle on 23 July 1972 (Freden, 1973). Orbital parameters are listed in Table 1.

TABLE 1. LANDSAT-1 ORBITAL PARAMETERS[a]

Orbit Parameter	Actual Orbit
Semi-major axis	7285.82 kilometers
Inclination	99.114 degrees
Period	103.267 minutes
Eccentricity	0.0006
Time at descending node (southbound equatorial crossing)	9:42 a.m.
Coverage cycle duration	18 days (251 revolutions)
Distance between adjacent ground tracks (at equator)	159.38 kilometers

[a] Adapted from Data Users Handbook (NASA, 1972).

The earth coverage pattern is shown in Figure 1 for two orbits on two consecutive days. Orbital parameters result in a 1.43 degree westward migration of the daily coverage swath, equivalent to a distance of 159 kilometers at the equator. The westward progression of the satellite revolutions continues, exposing all of the area between orbit N and orbit N+1 to the satellite sensors by day M. This constitutes one complete coverage cycle and consists of 251 revolutions. The cycle takes exactly 18 days and results in total global coverage between 81°N and 81°S latitude. Fourteen orbits (i.e., revolutions) are completed during each of 17 days in a cycle with 13 revolutions during one day (NASA, 1972). Approximately 188 scenes are acquired on an average day (Nordberg, 1972).


ORBIT N + 1, DAY M + 1
ORBIT N + 1, DAY M
ORBIT N, DAY M + 1
ORBIT N, DAY M
EQUATOR = 159 km

NOTE: ORBIT N, DAY M + 1
OCCURS 14 REVOLUTIONS
AFTER ORBIT N, DAY M

Figure 1. LANDSAT-1 ground coverage pattern. Adapted from Data Users Handbook (NASA, 1972).

LANDSAT-1 Instrumentation

The LANDSAT-1 payload consists of a Return Beam Vidicon (RBV) Camera Subsystem, a Multispectral Scanner Subsystem (MSS), and a Data Collection System (DCS). The RBV and MSS are designed to provide multispectral imagery of the earth beneath the observatory (*i.e.*, satellite). A malfunction occurred on 6 August 1972 (orbit 198) in the RBV power switching circuit and the RBV cameras were turned off as only one sensor system can be used in conjunction with the one functioning video tape recorder. The second recorder aboard the observatory malfunctioned between orbits 148 and 181 (Freden, 1973). The DCS serves to relay environmental information from geographically remote ground-based sensors to LANDSAT ground stations for processing and delivery to users. The RBV and DCS aspects of the satellite need not concern us.

The MSS is a line-scanning radiometer which collects data by creating images of the earth's surface in four spectral bands simultaneously through the same optical system. The instrument operates in the solar-reflected spectral band region from 500 to 1,100 nanometers. Scanner characteristics are listed in Table 2. The MSS scans cross-track swaths 185 kilometers in width, simultaneously imaging six scan lines for each of the four bands. The object plane is scanned by an oscillating flat mirror positioned between the scene and a double reflector telescope-type of optical chain. An 11.5 degree (Horan, Schwartz, and Love, 1974) cross-track field of view is produced by the mirror oscillating ±2.89 degrees about its nominal position (Figure 2).

A nominal orbital velocity of 6.47 kilometers per second, neglecting observatory perturbations and earth rotation effects, produces the requisite along-track scan. The subsatellite point moves 474 meters along the track during the 73.42 millisecond active scan-retrace cycle which is itself a consequence of the 13.62 hz mirror oscillation rate. The track distance of 474 meters synchronizes with the 474 meter along-track field of view of each set of six detectors. The line scanned by the first detector in one cycle of the active scan is in juxtaposition to the line scanned by the sixth detector of the previous scan (Figure 3).

Twenty-four glass optical fibers, arranged in a four by six (4x6) matrix in the focused area of the telescope, intercept the light from the earth scene. Light impinging on the square input end of each optical fiber is conducted to an individual detector through an optical filter unique to the respective spectral band under consideration. Photomultiplier tubes (PMT) serve as detectors for Bands Four through Six; Band Seven uses silicon photodiodes. A video signal is produced at the scanner electronics output as the image of a line across the swath is swept across the fiber during active scan. The signal is sampled at 9.95 microsecond (μsec) intervals which correspond to a 56 meter cross-track motion of the instantaneous field of view. The sampled signal is digitized and arranged into a serial digit data stream for transmission

TABLE 2. LANDSAT-1 MSS CHARACTERISTICS[a]

Item	Characteristics			
Telescope optics	22 cm (aperture diameter), f/3.6 Ritchey-Chretien			
Scanning method	Flat mirror oscillating ± 2.9 degrees at 13.62 Hz			
Scan (Swath) width	11.5 degrees (185 kilometers at 917 kilometers altitude)			
Scan duty cycle	44%			
Instantaneous field of view (IFOV)	86 microradians			
Number of bands	Four			
Number of lines (detectors) scanned per band	Six			
Limiting ground resolution from 917 kilometers altitude	40 meters			
Spectral band wavelength:				
NDPF Band Code				
Band 4 (Green)	500-600 nanometers			
Band 5 (Red)	600-700 nanometers			
Band 6 (Near-infrared One)	700-800 nanometers			
Band 7 (Near-infrared Two)	800-1,100 nanometers			
Sensor response:	Band 4	Band 5	Band 6	Band 7
Detector	PMT[b]	PMT	PMT	Photodiode
Nominal input for 4 V Scanner Output (10^{-4}W cm $^{-2}$sr^{-1})	24.8	20.0	17.6	46.0
Scanner and multiplexer weight	50 kilograms			
Signal channels	24			
Telemetry channels	97			
Command capability	72			
Scanner size	Approximately 36 x 38 x 89 cm			

---

[a] Adapted from Horan, et al. (1974).

[b] photomultiplier tube.

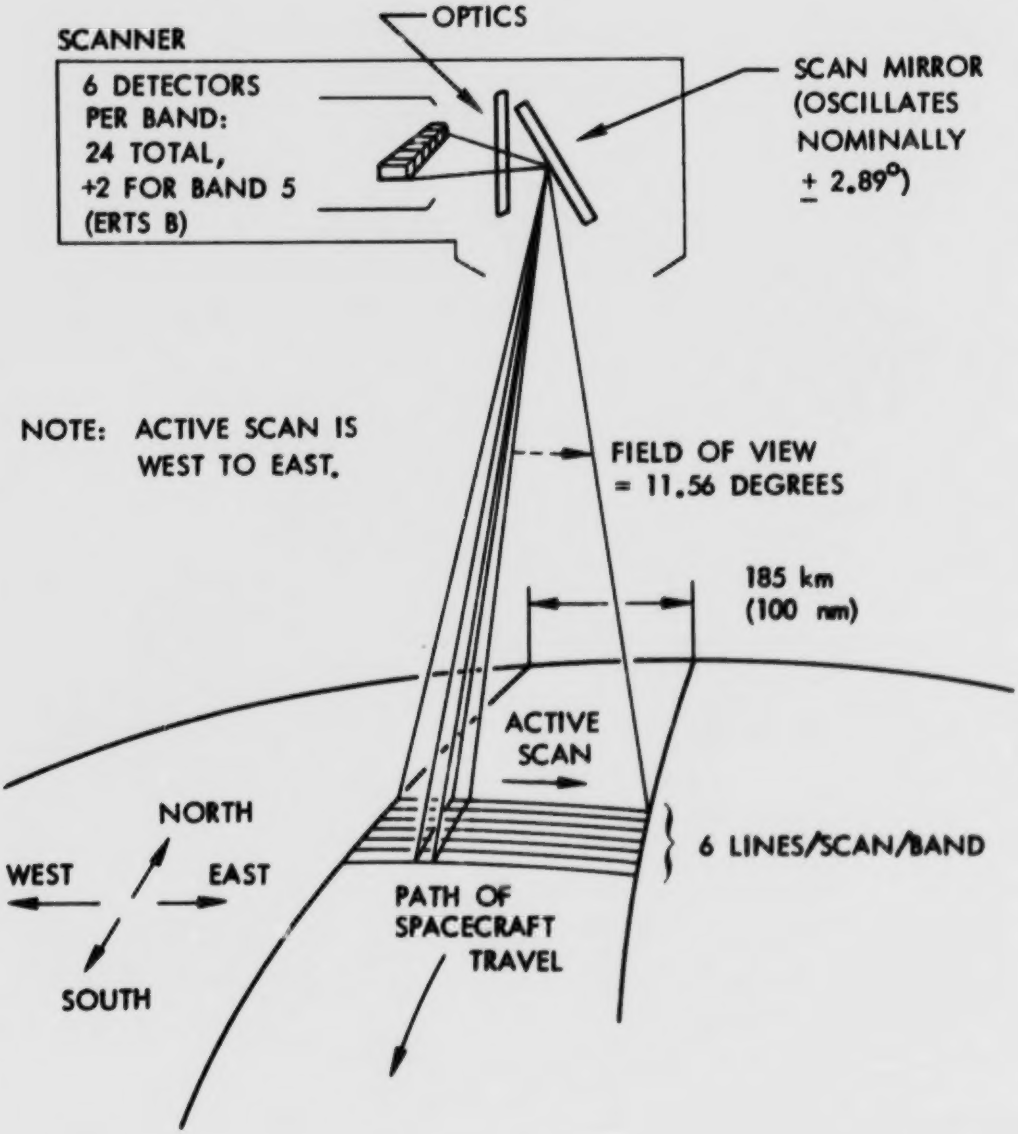

OPTICS
SCANNER
6 DETECTORS PER BAND: 24 TOTAL, +2 FOR BAND 5 (ERTS B)
SCAN MIRROR (OSCILLATES NOMINALLY ± 2.89°)
NOTE: ACTIVE SCAN IS WEST TO EAST.
FIELD OF VIEW = 11.56 DEGREES
185 km (100 nm)
ACTIVE SCAN
NORTH
WEST
EAST
SOUTH
6 LINES/SCAN/BAND
PATH OF SPACECRAFT TRAVEL

Figure 2. Schematic diagram of the LANDSAT-1 MSS scanning arrangement. Adapted from the Data Users Handbook (NASA, 1972).

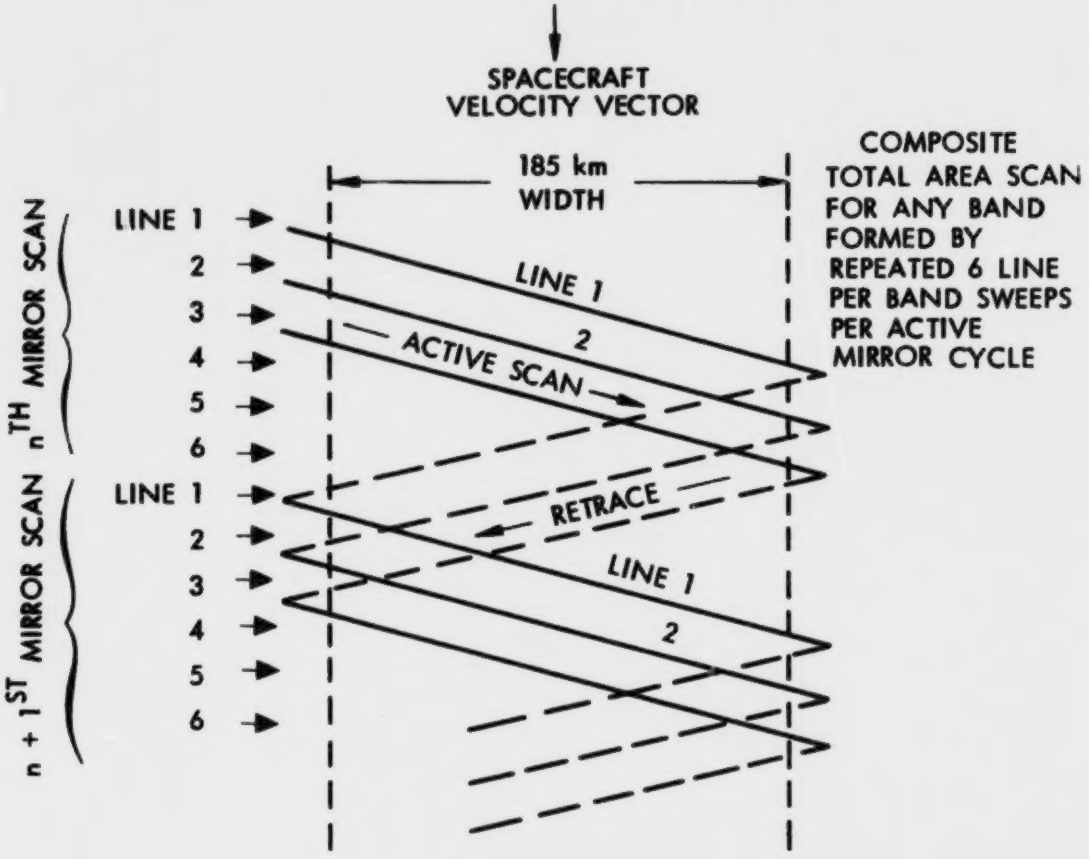

SPACECRAFT
VELOCITY VECTOR
185 km
WIDTH
COMPOSITE
TOTAL AREA SCAN
FOR ANY BAND
FORMED BY
REPEATED 6 LINE
PER BAND SWEEPS
PER ACTIVE
MIRROR CYCLE
n^{TH} MIRROR SCAN
LINE 1
2
3
4
5
6
$n + 1^{ST}$ MIRROR SCAN
LINE 1
2
3
4
5
6
LINE 1
2
ACTIVE SCAN
RETRACE
LINE 1
2

Figure 3. Ground scan pattern for a single MSS detector. Adapted from the Data Users Handbook (NASA, 1972).

to ground stations. Individual signals are derived from light passing through each fiber, resulting in 24 channels of output.

LANDSAT-1 Products

The electronic signals from the observatory's MSS are converted into photographic and computer products at the Goddard Space Flight Center, Greenbelt, Maryland. Third and fourth generation photographic products are available in the form of prints, positive and negative transparencies, and come in several scales including: 1:3,369,000; 1:1,000,000; 1:500,000; and 1:250,000 with the transparencies being limited to the two smaller scales. Color products are available for a relatively small number of scenes. Computer-compatible magnetic digital tapes (CCT's) may be requested in either a 7-track or a 9-track format. Four CCT's are required for the MSS data corresponding to one scene.

Copies of the CCT's and the photographic products are placed in the public domain at the Department of the Interior's Earth Resources Observations Systems (EROS) Data Center located in Sioux Falls, South Dakota.

LANDSAT-1 Lake Monitoring Potential

The advantages of using remote sensing imagery systems are threefold: they afford an overall (synoptic) view, they can give a time record, and they expand the spectral limits of the human eye (Scherz, et al., 1969; Scherz, 1971a; Scherz, 1971b). Multispectral satellite-borne imagery systems show promise as a means of monitoring and classifying the earth's lacustrine resources. This is partially due to the repetitive nature of a satellite and the tremendous synoptic view offered from orbital altitudes.

Visual examination of select frames of LANDSAT-1 MSS imagery from Wisconsin, Minnesota, and Florida suggest that good correlations may exist between the trophic status of lakes and their tonal characteristics. MSS Frame 1017-16093, recorded at an altitude of approximately 917 kilometers over southeastern Wisconsin and northeastern Illinois on 9 August 1972, will serve to illustrate this point.

Figure 4 is a reproduction of an EROS Data Center photograph of the scene as recorded in the near-infrared (IR2; 800 to 1,100 nanometers) spectral band. Water bodies, including the larger streams, stand out boldly against the lighter tones of the land features. The labelled lakes, excluding Lake Michigan, were sampled by the U.S. Environmental Protection Agency's National Eutrophication Survey (NES) during the 1972 open water season. Gray tone differences are not evident among the lakes nor are tonal patterns visible on any of the lakes. IR2 is, however, a good spectral band for the location and demarcation of water bodies. Some caution is necessary when conducting a lake enumeration on the photograph because some of the "lakes" are in reality shadows cast by cumulus clouds.

Figure 5 is the same scene recorded in near-infrared one (IR1; 700 to 800 nanometers). Tonal differences are apparent, at least in the original photographic print, among the lakes, and patterns are evident on some of the lakes (e.g., Lake Koshkonong). Lakes are readily located and their boundaries delimited in this band.

Figure 6 is a red light (RED; 600 to 700 nanometers) MSS photograph of the scene. Marked gray tone differences are apparent among the lakes. Lakes commonly recognized as eutrophic (e.g., Lake Como) tend to appear light in tone and meld in with the land features. Lakes with relatively good water quality (e.g., Lake Geneva) are characterized by darker tones. Lotic bodies are not readily apparent in the photograph.

The green light (GRN; 500 to 600 nanometers) sensed by the MSS was used to construct the Figure 7 photograph. Although the lakes are difficult to discern, a result of low contrast among the scene elements, differences among the lakes can be detected with the unaided eye.

It is apparent, from the visual examination of LANDSAT-1 MSS Frame 1017-16093 and other frames from several additional states, that the satellite-borne multispectral scanner is collecting data which may be of value in the classification and monitoring of lentic bodies. The results of the examination suggest that GRN, RED, and IR1 contain most of the information relative to trophic status assessment.

DESCRIPTION OF THE STUDY AREA

Many current efforts to determine the feasibility of using LANDSAT-1 MSS data in water quality monitoring tend to be intensive in nature, near-real time, and oriented toward the dymanics of pollution or eutrophication (e.g., Chase and Smith, 1973; Lind and Henson, 1973; Lind, 1973). The investigations are very limited in geographic scope, typically involving fewer than six water bodies.

Another approach, the one used in this report, involves the examination of a relatively large number of lakes over a more extensive geographic area. Although it is not uncommon to find lakes of different trophic state within the same lake region (e.g., Southeastern Lake District of Wisconsin), the selection of a larger study area affords the opportunity to include lakes exhibiting a greater trophic range. In addition, assuming that lakes have characteristic multispectral signatures at particular points on the trophic scale, the use of a larger and more diverse lake population permits a more extensive evaluation of the LANDSAT-1 MSS's capabilities in the realm of lake monitoring and classification.

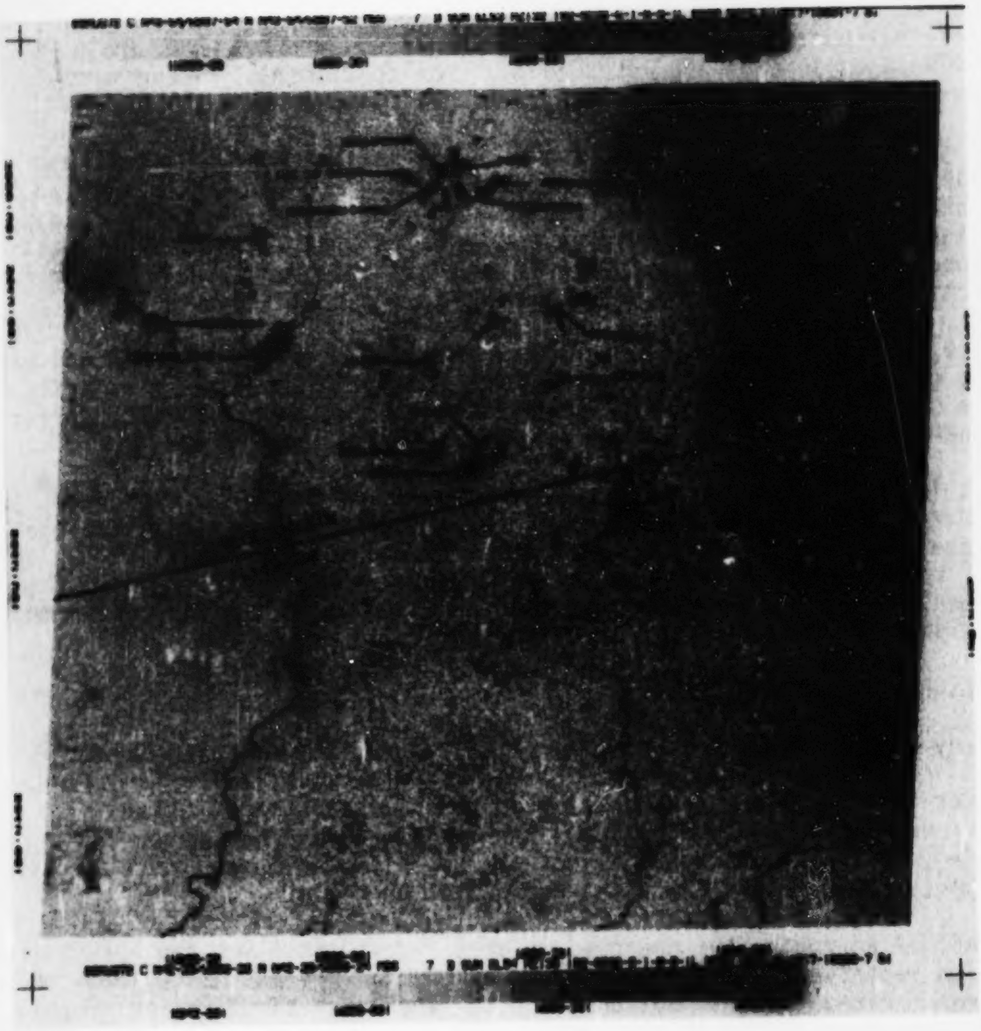


Figure 4. Reproduction of an EROS Data Center IR2 print of Frame 1017-16093 (9 August 1972). Water bodies stand out in stark contrast to the lighter-toned land features. The labelled lakes, excluding Lake Michigan, were sampled by the National Eutrophication Survey during 1972. The reproduction, originally printed at a scale of 1:1,000,000, has a scale of approximately 1:1,415,000.

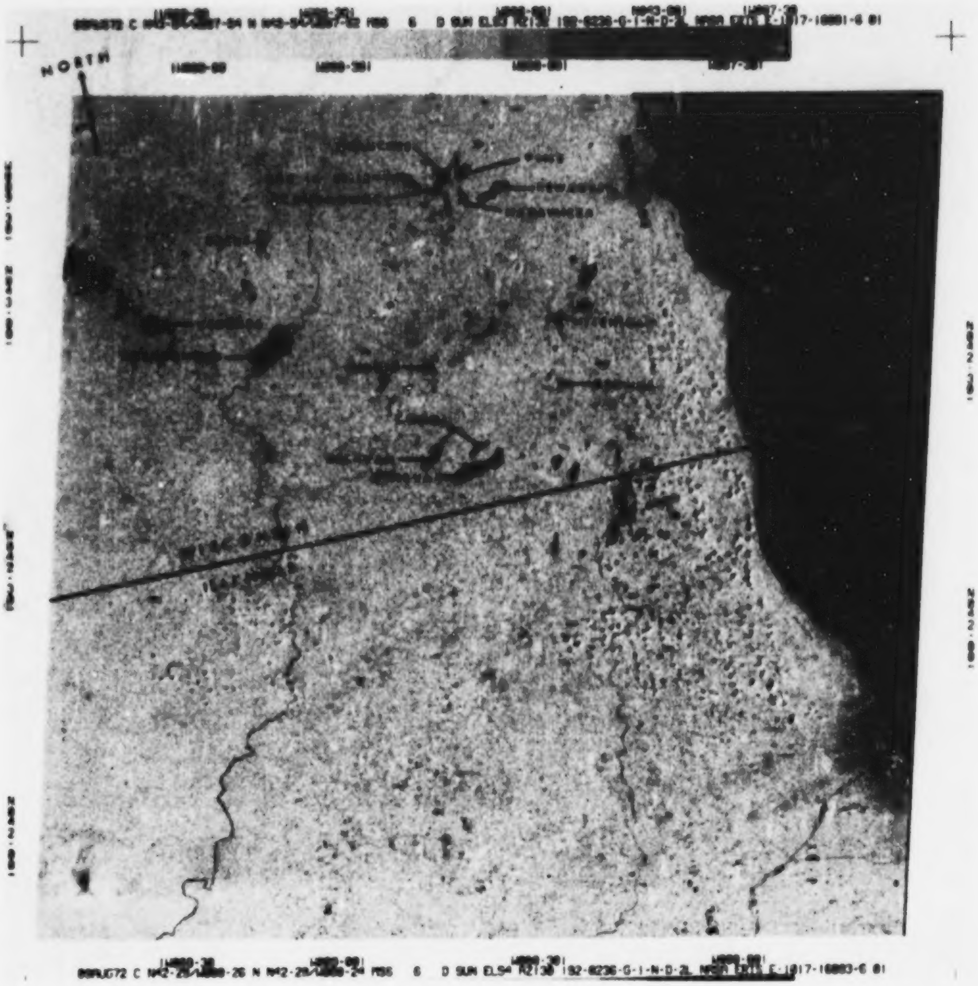


Figure 5. Reproduction of EROS IR1 print of Frame 1017-16093 (9 August 1972). Surface patterns are evident on some of the lakes (e.g., Lake Koshkonong). Each edge of the picture is equivalent to a ground distance of approximately 185 kilometers. The reproduction is printed at a scale approximating 1:1,415,000.

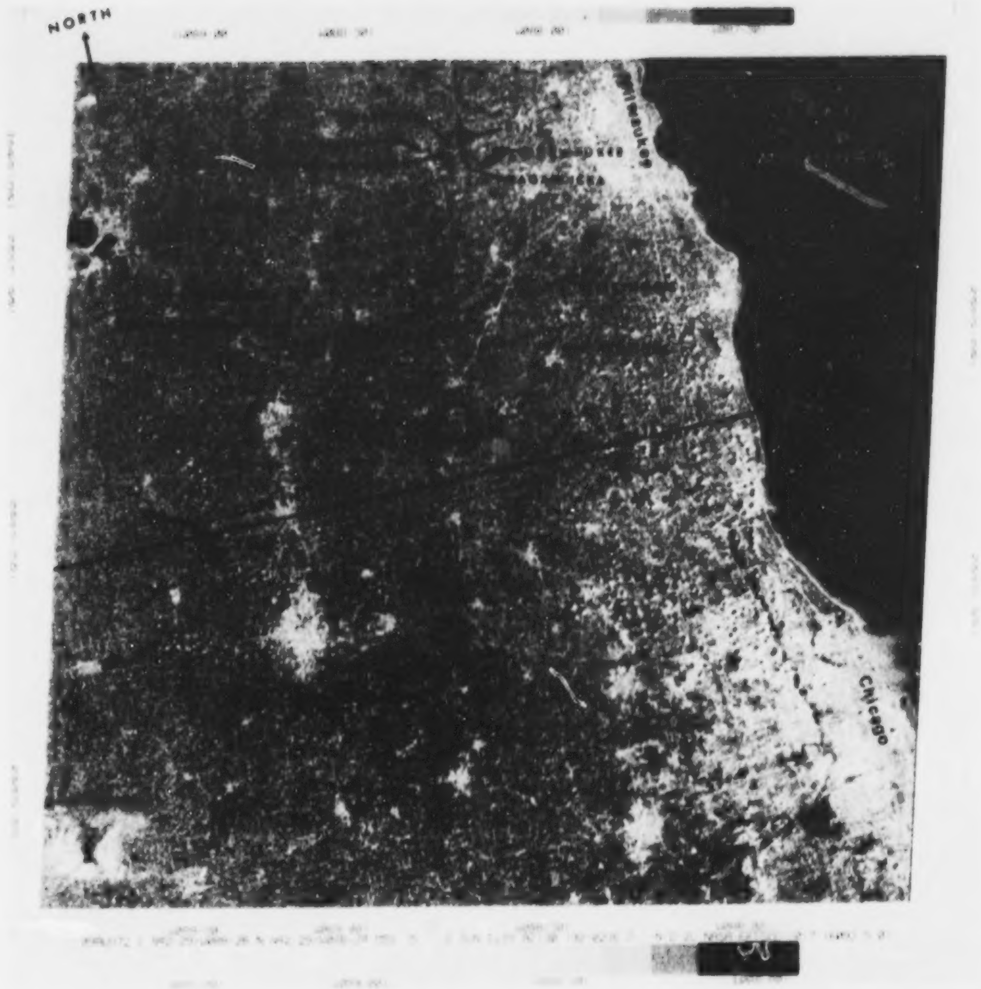


Figure 6. Reproduction of EROS RED (MSS Band 5) print of Frame 1017-16093 (9 August 1972). Variations in gray tone are readily apparent among the lakes and suggest differences in water quality. Lake Geneva, characterized by relatively high water quality, is dark in tone compared with, for example, eutrophic Lake Koshkonong. The small ball-like white objects between Milwaukee and Chicago are cumulus clouds. The reproduction is printed at a scale of approximately 1:1,415,000.

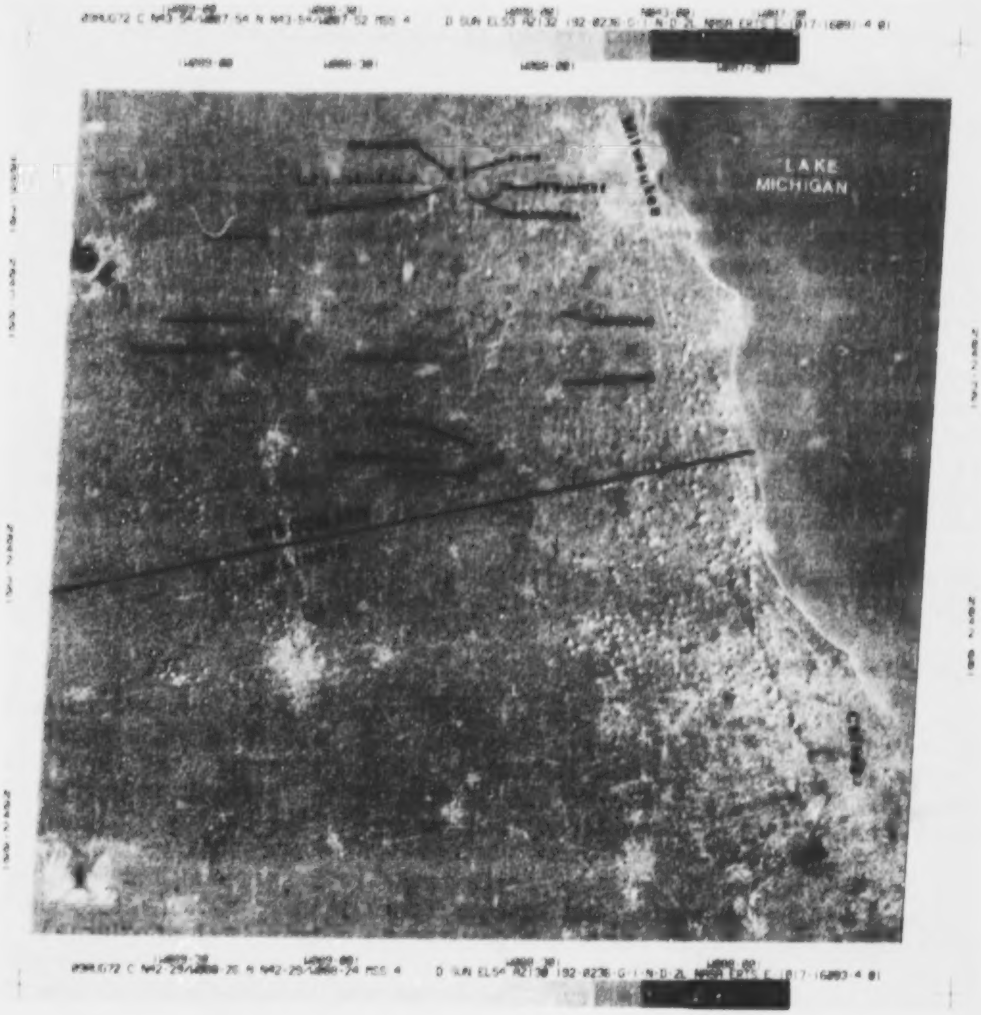

Milwaukee
LAKE MICHIGAN
Chicago

Figure 7. Reproduction of EROS GRN (MSS Band 4) print of Frame 1017-16093 (9 August 1972). Scenes recorded in the green band generally lack contrast, but contain information useful in monitoring earth resources. The reproduction is printed at a scale of 1:1,415,000.

Geographic Area

The geographic area serving as a matrix for the study lakes comprises the states of Minnesota, Wisconsin, Michigan, and New York. The area was selected for its abundance of lakes, the availability of pertinent environmental (*i.e.*, ground truth) data and concurrent or near-concurrent LANDSAT-1 MSS frames.

Climate

The climate of the study area is humid continental. Continental polar air masses dominate during the winter, resulting in a mean temperature of less than -10°C for the coldest month. Most of the study lakes are ice-bound for several months, two notable exceptions being the New York Finger Lakes, Seneca and Cayuga, which usually remain open and in full circulation throughout the winter (Berg, 1963). Tropical air masses dominate during the summer and high temperatures prevail. The warmest month has a mean temperature in excess of 18°C. The temperature extremes are less severe in the eastern portion of the study area (New York). Although precipitation is common throughout the year, a summer maximum exists. The mean annual precipitation ranges from a low of approximately 50 centimeters in northwestern Minnesota to a high of about 125 centimeters in north central New York (USGS, 1970).

Detailed descriptions of the climate are found in Trewartha (1968), USDA (1941), Visher (1954), Thornthwaite (1948), and Strahler (1969).

Geology, Soils, and Land Use

The study area extends over three physiographic divisions and includes seven subdivisions (Figure 8). The entire area, excluding a small region in western Wisconsin and southeastern Minnesota (the "Driftless Area"), was exposed to the forces of continental glaciation which were instrumental in the formation of the numerous lake basins.

The bedrock ranges in age from Precambrian to Cretaceous and includes sedimentary, metamorphic, and igneous rocks (Figure 9). Areas underlain with older Precambrian rocks and covered by a thin veil of glacial drift (*e.g.*, northeastern Minnesota) generally have lakes possessing relatively high water quality. The landscape is dominanted by the members of six soil orders (7th Approximation) including Alfisols, Entisols, Histosols, Inceptisols, Mollisols, and Spodosols (Figure 10). Major types of land use are shown in Figure 11. Lakes seriously modified by man are generally found in areas where land use is chiefly agricultural in nature, particularly as cropland.

Lake Selection Criteria and Location

Most of the lakes incorporated into this study were selected from some 220 lakes sampled in 1972 by the U.S. Environmental Protection Agency's (EPA) National Eutrophication Survey (NES). The lakes were selected,

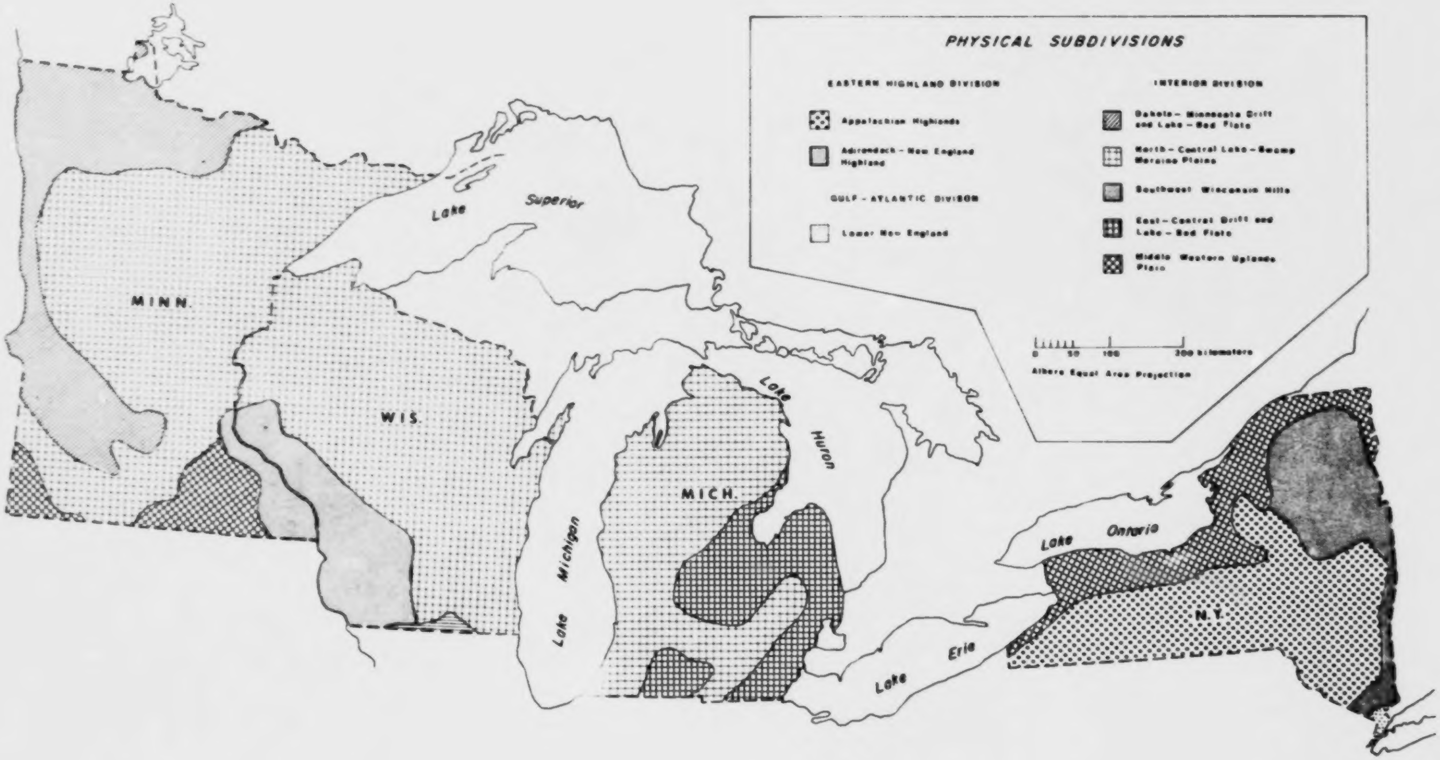
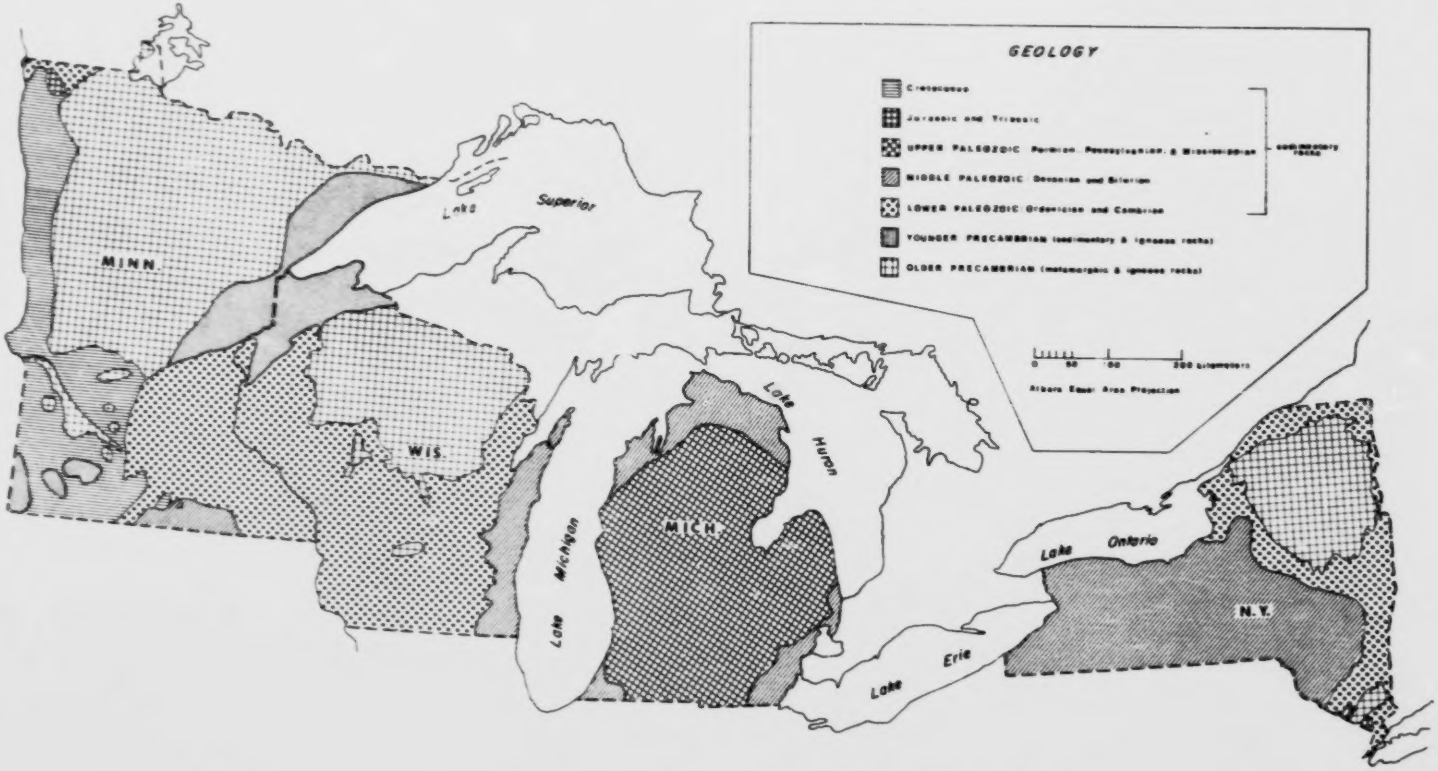

PHYSICAL SUBDIVISIONS
EASTERN HIGHLAND DIVISION
Appalachian Highlands
Adirondack - New England Highland
GULF - ATLANTIC DIVISION
Lower New England
INTERIOR DIVISION
Dakota - Minnesota Drift and Lake - Bed Flats
North - Central Lake - Swamp Moraine Plains
Southwest Wisconsin Hills
East - Central Drift and Lake - Bed Flats
Middle Western Upland Plain
0 50 100 200 kilometers
Albers Equal Area Projection
MINN.
WIS.
MICH.
N.Y.
Lake Superior
Lake Michigan
Lake Huron
Lake Erie
Lake Ontario

Figure 8. Physical subdivisions. Adapted from U.S. Geological Survey (1970) and Hammond (1964).



GEOLOGY
Cretaceous
Jurassic and Triassic
UPPER PALEOZOIC Permian, Pennsylvanian, & Mississippian
MIDDLE PALEOZOIC Devonian and Silurian
LOWER PALEOZOIC Ordovician and Cambrian
sedimentary rocks
YOUNGER PRECAMBRIAN (sedimentary & igneous rocks)
OLDER PRECAMBRIAN (metamorphic & igneous rocks)
0 50 100 200 kilometers
Albers Equal Area Projection
MINN.
WIS.
MICH.
N.Y.
Lake Superior
Lake Michigan
Lake Huron
Lake Erie
Lake Ontario

Figure 9. Geology. Adapted from U.S. Geological Survey (1970). For greater detail see U.S. Geological Survey (1965), Geologic Map of North America, 1:5,000,000.

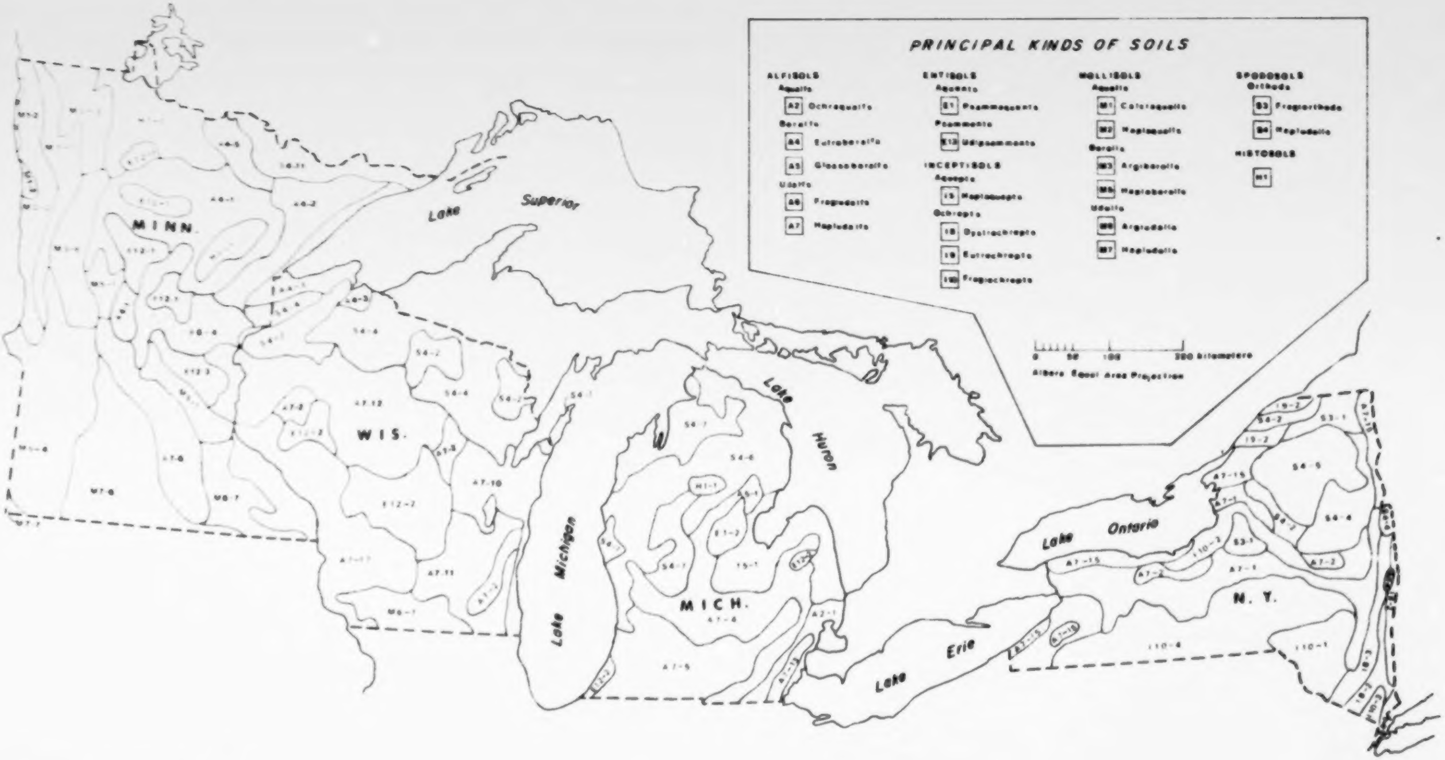

PRINCIPAL KINDS OF SOILS
ALFISOLS
Aqualfs
A2 Ochraqualfs
Boralfs
A4 Eutroboralfs
A5 Glossoboralfs
Udalfs
A6 Fragiudalfs
A7 Hapludalfs
ENTISOLS
Aquents
E1 Psammaquents
Psamments
E12 Udipsamments
INCEPTISOLS
Aquepts
I5 Haplaquepts
Ochrepts
I8 Dystrochrepts
I9 Eutrochrepts
I10 Fragiochrepts
MOLLISOLS
Aquolls
M1 Calciaquolls
M2 Haplaquolls
Borolls
M3 Argiborolls
M5 Haploborolls
Udolls
M6 Argiudolls
M7 Hapludolls
SPODOSOLS
Orthods
S3 Fragiorthods
S4 Haplorthods
HISTOSOLS
H1
0 50 100 200 kilometers
Albers Equal Area Projection
MINN.
WIS.
MICH.
N. Y.
Lake Superior
Lake Michigan
Lake Huron
Lake Erie
Lake Ontario

Figure 10. Distribution of principal kinds of soils: Orders, Suborders, and Great Groups. The letter-number symbols in the legend are abbreviated from those on the map. For a complete description, see U.S. Geological Survey (1970). Complete definitions of the soils are found in Soil Classification, A Comprehensive System, 7th Approximation (U.S. Department of Agriculture, 1960) and (USDA, March 1967) Supplement. The map is adapted from U.S. Geological Survey (1970).

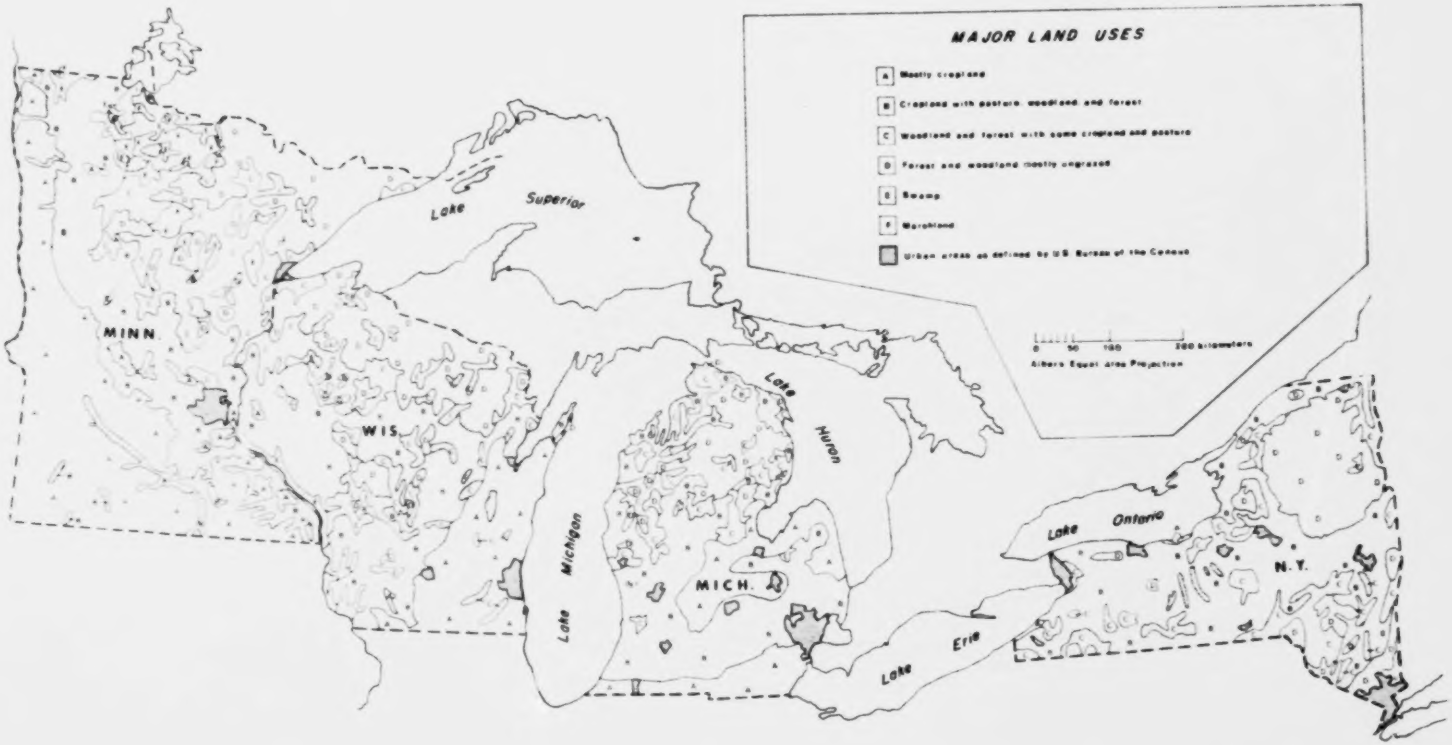

MAJOR LAND USES
A Mostly cropland
B Cropland with pasture, woodland and forest
C Woodland and forest with some cropland and pasture
D Forest and woodland mostly ungrazed
E Swamp
F Marshland
Urban areas as defined by U.S. Bureau of the Census
0 50 100 200 kilometers
Albers Equal Area Projection
MINN.
WIS.
MICH.
N.Y.
Lake Superior
Lake Michigan
Lake Huron
Lake Erie
Lake Ontario

Figure 11. Major land uses. Adapted from U.S. Geological Survey (1970).

for the purposes of this report, to give extensive geographic coverage, trophic indicator values that covered a range representative of the 1972 NES-sampled lakes, and for completeness of sampling records. The study lakes are listed in Table 3. NES-sampled lakes have both a serial number and a STORET (STOrage and RETrieval) number; those with only a serial number are outside the scope of NES. Lake locations are depicted in Figure 12.

GROUND TRUTH COLLECTION

Each NES lake (serial numbers 1-100) was sampled three times (spring, summer, fall) during the 1972 calendar year (Appendix B) by helicopter-borne sampling teams operating from pontoon-equipped Bell UL-1H aircraft. The helicopters were equipped with a submersible pump and appropriate sensors for _in situ_ measurements of conductivity, temperature, optical transmissivity, dissolved oxygen, hydrogen-ion concentrations (pH), and water depth. Additional equipment included an echo sounder, 30 cm Secchi disc, and water sampling equipment.

Lake Site Selection

Lake sampling sites were selected on the basis of lake morphometry, and potential major sources of nutrient input, as well as the on-site judgment of the sampling team's limnologists. The number of sampling sites varied for different lakes, ranging from one to nine (Lake Winnebago).

Lake Sampling Methods

After landing on the lake surface in the general area of a sampling site, the helicopter was taxied to locate the deepest nearby water. There a small reference bouy was deployed to aid the pilot in maintaining his station. Observations were recorded relating to general lake appearance, phytoplankton bloom conditions, aquatic macrophytes, and shoreline developments (_e.g._, residential units) along with magnetic compass bearings to prominent landmarks. A photograph was taken of the site, including the reference buoy and the prominent landmarks to assure return to the same site on subsequent sampling rounds.

Secchi disc transparency readings were made and water samples were bucket-dipped from the lake surface. The sensor recorders were monitored as the sensor-pump package was slowly lowered through the water column, permitting the limnologists to select depths or levels to be sampled as the package was winched to the surface. After touching bottom, the package was raised to a point approximately 1.2 meters off the bottom.* Each sensor's digital output was recorded and the submersible pump activated for the collection of water samples. The package was then raised to the next sampling level and the process was repeated.

---

* In 1972 the sensor could be deployed to a maximum depth of about 114 meters.

TABLE 3. STUDY LAKES

Lake Name	Serial Number[a]	STORET Number	County	Lake Coordinates[b]	
				N. Latitude	W. Longitude
Blackduck	1	2711	Beltrami	47° 45' 30"	94° 36' 00"
Bemidji	2	27C1	Beltrami	47° 29' 30"	94° 50' 00"
Andrusia	3	27C0	Beltrami	47° 26' 30"	94° 38' 30"
Wolf	4	27A2	Becker	47° 26' 30"	94° 40' 30"
Cass	5	2715	Cass	47° 27' 00"	94° 28' 30"
Leech	6	2746	Cass	47° 15' 00"	94° 13' 00"
Birch	7	2710	Cass	46° 56' 00"	94° 31' 30"
Trout	8	2793	Itasca	47° 17' 00"	93° 25' 00"
Mashkenode	9	2756	St. Louis	47° 29' 30"	94° 36' 00"
Whitewater	10	2749	St. Louis	47° 29' 30"	92° 11' 00"
Pelican	11	2765	Crow Wing/ St. Louis	48° 02' 00"	92° 50' 00"
Shagawa	12	2780	St. Louis	47° 55' 00"	91° 53' 00"
Gull	13	2737	Cass	46° 25' 00"	94° 21' 30"
Rabbit	14	2771	Crow Wing	46° 31' 30"	93° 56' 00"
Cranberry	15	2720	Crow Wing	46° 24' 00"	93° 46' 30"
Darling	16	27B4	Douglas	45° 56' 00"	95° 23' 00"
Carlos	17	27B9	Douglas	45° 56' 00"	95° 23' 00"
Le Homme Dieu	18	27B5	Douglas	45° 56' 30"	95° 21' 30"
Minnewaska	19	2761	Hennepin/ Pope	45° 36' 30"	95° 32' 00"
Nest	20	27B3	Kandiyohi	45° 16' 00"	95° 56' 00"
Green	21	27B2	Kandiyohi	45° 16' 00"	94° 52' 00"
Wagonga	22	27B1	Kandiyohi	45° 04' 00"	94° 56' 30"
Clearwater	23	2716	Wright/ Stearns	45° 20' 00"	94° 07' 00"
Mud (at Maple Lake)	24	2753	Wright	45° 13' 30"	93° 59' 00"
Cokato	25	2719	Wright	45° 07' 00"	94° 09' 30"
Buffalo	26	2713	Wright	45° 08' 30"	93° 54' 30"
Carrigan	27	2714	Wright	45° 03' 30"	93° 57' 30"
Silver	28	2782	McLeod	44° 53' 00"	94° 13' 00"
Minnetonka	29	2760	Hennepin	44° 57' 30"	93° 30' 30"
Forest	30	27A9	Washington	45° 17' 30"	92° 58' 30"
White Bear	31	27B0	Washington	45° 04' 00"	92° 58' 30"
St. Croix	32	27A7	Washington	44° 46' 00"	92° 49' 00"
Spring	33	27A6	Washington	44° 45' 30"	92° 52' 30"
Pepin	34	27A4	Goodhue	44° 23' 00"	92° 02' 00"
Madison	35	2750	Blue Earth	44° 10' 30"	93° 49' 00"
Sakatah	36	2777	Le Sueur	44° 14' 00"	93° 27' 30"
Bear	37	2706	Freeborn	43° 33' 00"	93° 30' 00"
Albert Lea	38	2702	Freeborn	43° 37' 00"	93° 17' 30"
Yellow	39	5576	Burnett	45° 55' 30"	92° 25' 00"
Wapogasset	40	5550	Polk	45° 19' 30"	92° 26' 30"

TABLE 3. STUDY LAKES (continued)

Lake Name	Serial Number[a]	STORET Number	County	Lake Coordinates[b]	
				N. Latitude	W. Longitude
Long	41	5573	Price	45° 42' 00"	90° 27' 00"
Elk	42	5575	Price	45° 42' 00"	90° 24' 30"
Trout	43	5572	Vilas	46° 04' 00"	89° 40' 00"
Crystal	44	5571	Vilas	46° 00' 00"	89° 36' 39"
Tainter	45	5546	Dunn	44° 56' 00"	91° 53' 30"
Shawano	46	5539	Shawano	44° 47' 30"	88° 34' 00"
Poygan	47	5538	Winnebago	44° 06' 30"	88° 42' 30"
Butte Des Morts	48	5508	Winnebago	44° 02' 00"	88° 34' 00"
Winnebago	49	5554	Winnebago/ Fond Du Lac	44° 12' 00"	88° 27' 30"
Round	50	5566	Waupaca	44° 20' 00"	89° 10' 00"
Green	51	5519	Fond Du Lac	43° 51' 30"	88° 57' 00"
Swan	52	5545	Columbia	45° 32' 30"	89° 23' 30"
Beaver Dam	53	5503	Dodge	43° 27' 30"	88° 50' 30"
Kegonsa	54	5520	Dane	42° 58' 00"	89° 13' 30"
Rock	55	5564	Vilas	43° 04' 30"	88° 55' 00"
Koshkonong	56	5522	Dane/ Jefferson	42° 50' 00"	89° 01' 30"
Lac La Belle	57	5563	Waukesha	43° 07' 00"	88° 31' 00"
Oconomowoc	58	5532	Waukesha	43° 05' 30"	88° 28' 30"
Okauchee	59	5580	Waukesha	43° 06' 30"	88° 28' 30"
Pine	60	5536	Waukesha	43° 07' 00"	88° 23' 30"
Nagawicka	61	5531	Price	44° 04' 00"	88° 24' 30"
Pewaukee	62	5557	Waukesha	43° 05' 00"	88° 16' 00"
Tichigan	63	5559	Racine	42° 46' 00"	88° 13' 00"
Browns	64	5560	Racine	42° 41' 00"	88° 14' 30"
Middle	65	5569	Walworth	42° 46' 30"	88° 34' 00"
Delavan	66	5513	Walworth	42° 37' 00"	88° 37' 30"
Como	67	5562	Walworth	42° 37' 00"	88° 27' 30"
Geneva	68	5561	Walworth	42° 36' 00"	88° 26' 00"
Charlevoix	69	2617	Charlevoix	45° 19' 00"	85° 15' 00"
Higgins	70	2695	Roscommon/ Crawford	44° 26' 00"	84° 40' 30"
Houghton	71	2696	Roscommon	44° 24' 30"	84° 47' 30"
Pere Marquette	72	2698	Mason	43° 56' 30"	86° 27' 00"
White	73	2688	Muskegon/ Newaygo	43° 22' 30"	86° 25' 30"
Muskegon	74	2659	Newaygo/ Muskegon	43° 14' 00"	86° 20' 00"
Fremont	75	2631	Newaygo	43° 26' 30"	85° 58' 30"
Mona	76	2691	Muskegon	43° 10' 00"	86° 17' 30"
Crystal	77	2694	Montcalm	43° 16' 30"	84° 55' 30"

TABLE 3. STUDY LAKES (continued)

Lake Name	Serial Number[a]	STORET Number	County	Lake Coordinates[b] N. Latitude	Lake Coordinates[b] W. Longitude
Jordan	78	2640	Ionia/Barry	42° 45' 30"	85° 09' 00"
Thornapple	79	2683	Barry	42° 37' 00"	85° 21' 30"
Strawberry	80	2699	Livingston	42° 26' 30"	83° 51' 00"
Chemung	81	2618	Livingston	42° 35' 30"	83° 51' 30"
Thompson	82	2697	Livingston	42° 37' 30"	83° 55' 30"
Ford	83	2629	Washtenaw	42° 12' 30"	83° 33' 30"
Union	84	2685	Branch/Calhoun	42° 02' 30"	85° 12' 30"
Long	85	2692	Ottawa	41° 55' 30"	84° 20' 00"
Randall	86	2671	Branch	42° 00' 30"	85° 02' 30"
Schroon	87	3624	Warren/Essex	43° 50' 00"	73° 47' 00"
Black	88	3602	Jefferson/St. Lawrence	44° 36' 00"	75° 28' 30"
Cassadaga	89	3607	Chautauqua	42° 20' 30"	79° 19' 30"
Chautauqua	90	3610	Chautauqua	42° 06' 00"	79° 15' 00"
Conesus	91	3639	Livingston	42° 50' 00"	77° 42' 30"
Canandaigua	92	3604	Ontario	42° 53' 30"	77° 15' 30"
Keuka	93	3617	Steuben/Yates	42° 39' 30"	77° 09' 00"
Seneca	94	3635	Yates/Senga/Schuler	42° 56' 30"	76° 52' 00"
Cayuga	95	3608	Cayuga/Tompkins/Seneca	42° 58' 00"	76° 44' 30"
Owasco	96	3627	Cayuga	42° 47' 00"	76° 29' 00"
Cross	97	3611	Cayuga	43° 06' 00"	76° 25' 30"
Otter	98	3625	Cayuga	43° 09' 30"	76° 33' 00"
Round	99	3630	Saratoga	42° 55' 00"	73° 45' 00"
Saratoga	100	3633	Saratoga	43° 04' 30"	73° 41' 00"
Winona	101	27A1	Douglas	45° 33' 30"	95° 23' 00"
Trace	102	2792	Todd	45° 50' 30"	94° 45' 30"
Calhoun	103	27B6	Hennepin	44° 56' 00"	93° 18' 30"
Big Stone	104	2709	Big Stone	45° 18' 00"	94° 27' 00"
Zumbro	105	27A5	Olmsted	44° 14' 00"	92° 29' 00"
Oneida	106	3622	Oswego/Oneida	43° 11' 00"	75° 45' 30"
Canadarago	107	3603	Otsego	42° 50' 00"	75° 00' 00"
Mendota	108		Dane	43° 11' 00"	89° 13' 00"
Monona	109		Dane	43° 08' 30"	89° 16' 00"
Waubesa	110		Dane	43° 01' 30"	89° 29' 30"
Cottonwood	111	27C3	Lyon	44° 36' 00"	95° 40' 00"
Maple	241		Wright	45° 13' 30"	93° 59' 30"

---

[a] The lakes with the serial numbers 1-31, 33, 35-38, 101-103, 111, and 241 are wholly contained in Minnesota. Lakes 32, 34, and 105, located on the borders of the state, are referred to as "Minnesota" lakes for convenience. Lakes 39-68 and 108-110 are Wisconsin lakes; 69-86 are in Michigan. New York lakes have been assigned the numbers 87-100 and 106-107.

[b] In the case of seepage lakes, the geographic coordinates represent a point on the lake surface.

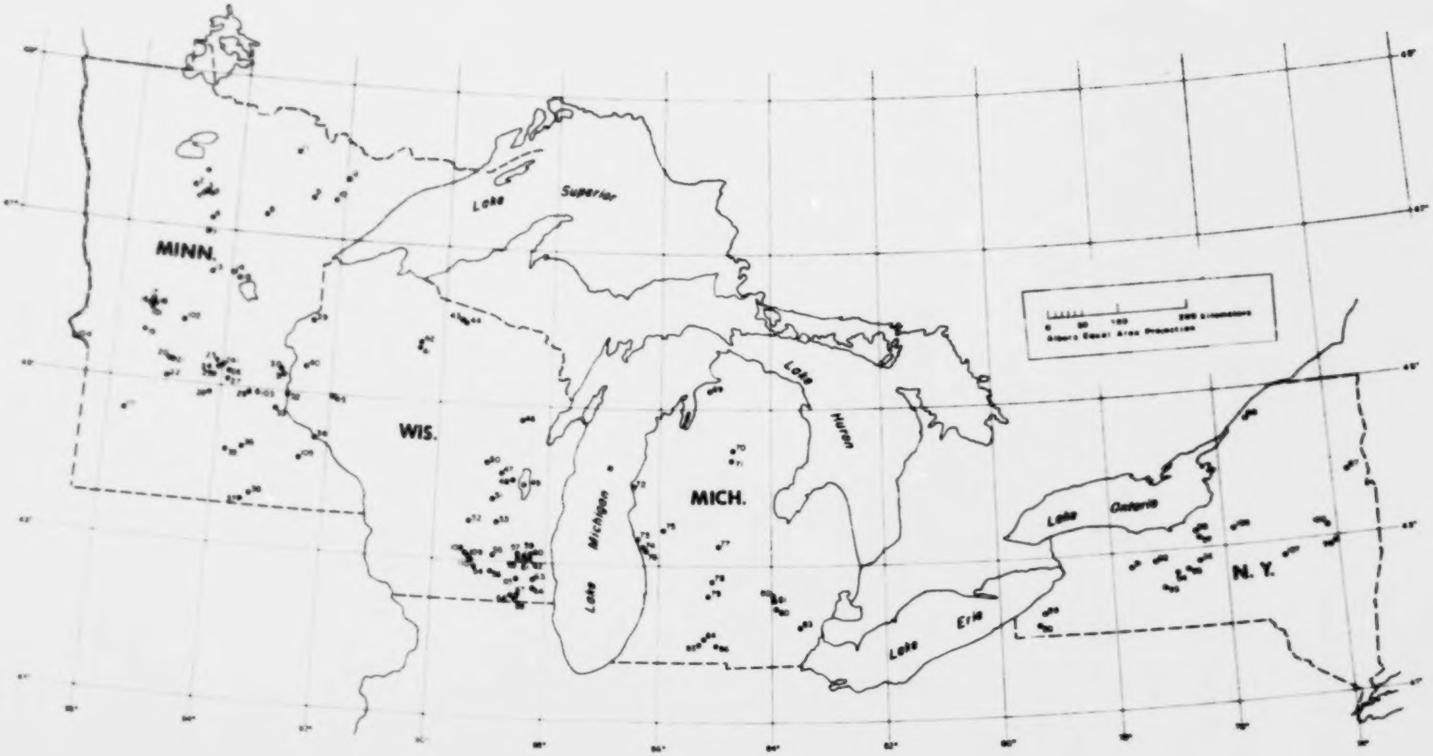

MINN.
WIS.
MICH.
N. Y.
Lake Superior
Lake Michigan
Lake Huron
Lake Erie
Lake Ontario
0
50
100
200 Kilometers
Albers Equal Area Projection

Figure 12. Location of the study lakes. The lakes with serial numbers 1-100 were used in the cluster analyses and principal component ordination analyses.

The procedure was continued until all of the selected levels were sampled.

Water samples were collected from each selected depth for nutrient, alkalinity, pH, conductivity, and dissolved oxygen determinations. The samples collected for alkalinity, nitrate-nitrogen, nitrite-nitrogen, ammonia-nitrogen, and dissolved phosphorus were preserved on-site by the addition of 40 mg/l of mercuric chloride. The samples were filtered through a 0.45 micrometer membrane filter (prerinsed with de-ionized water) and the filtrate was shipped to EPA's National Environmental Research Center (NERC), Las Vegas, Nevada. The samples for total phosphorus determination were preserved with a 40 mg/l mercuric chloride solution, but were not filtered.

Integrated samples for algae enumeration and identification purposes and chlorophyll a determination were collected by raising or lowering the package while continuing to operate the pump. The package movement was timed to provide a water sample representative of the water column from the surface to approximately 4.6 meters, or to a point just above the bottom in water less than 4.6 meters in depth. The algae samples were fixed with Lugol's solution and forwarded to NERC-Las Vegas.

A 18.9-liter water sample, composited from water collected at each sampling depth and every sampling site (i.e., station) during the fall sampling period, was airmailed to the Pacific Northwest Environmental Research Laboratory (PNERL), Corvallis, Oregon, for the determination of its productivity potential under a set of standard conditions. The unpreserved sample, unrefrigerated while in transit, was stored in a freezer until the analysis could commence.

Analytical Methods

The water samples for dissolved oxygen, pH, and chlorophyll a determinations were analyzed in a mobile field laboratory at the end of each day of sampling. The dissolved oxygen water samples, fixed and acidified aboard the helicopters, were titrated with phenylarsine oxide in conjunction with a starch indicator. A Beckman Field Laboratory pH meter was used to determine the hydrogen-ion concentration of the water samples. The samples were refrigerated until they were analyzed.

The samples for chlorophyll a determination were refrigerated in the dark and were analyzed using the fluorometric procedure described by Yentch and Menzel (1963). Algal identification and enumeration included total cell count (Sedgewick-Rafter) and a differential count and identification of the five most abundant genera of algae.

Ammonia-nitrogen, nitrate-nitrogen, nitrite-nitrogen, dissolved phosphorus, total phosphorus, and alkalinity were measured at NERC-Las Vegas with a Technicon Autoanalyzer II according to the general methodology described in Working Paper Number 1 (NES, 1974).

The procedures used in the algal assay test, a methodology for the determination of a water sample's productivity potential and limiting nutrients, were those outlined in EPA's National Eutrophication Research Program's publication entitled "Algal Assay Procedure Bottle Test" (U.S. EPA, 1971). The analyses were conducted at PNERL, NERC-Corvallis.

SECTION IV

LAKE CLASSIFICATION

There is far from universal agreement as to what constitutes a lake. Veatch and Humphrys (1966) suggested that to give the word "lake" a precise, limited meaning would probably be an exercise in futility because the word has been in use for a long time and been given a diversity of applications. The word is used as a synonym for pond, reservoir, and sea. It has been applied to bodies of fresh water and saline water; to standing water and widenings in rivers; to bodies of water measuring less than a hectare and to those gauged in hundreds of thousands of hectares; to naturally occurring water bodies and man-made reservoirs; to water-filled or partially filled basins; and to basins void of water. "Lake" is generally more prestigious than other common names (*e.g.*, pond) and is preferred by promoters of water-based tourist and recreational businesses and commercial developers of shoreline property (Veatch and Humphrys, 1966). Nevertheless, numerous attempts have been made to define and delimit the members of lentic series (*i.e.*, lake, pond, marsh, and their intergrades).

Forel defined a lake as a body of standing water occupying a basin and lacking continuity with the sea; he defined a pond as a lake of slight depth (Welch, 1952). Welch (1952) defined a lake as a "...body of standing water completely isolated from the sea and having an area of open, relatively deep water sufficiently large to produce somewhere on its periphery a barren, wave-swept shore." He employed the term "pond" "...for that class of very small, very shallow bodies of standing water in which quiet water and extensive occupancy by higher aquatic plants are common characteristics" and suggested that all larger bodies of standing water be referred to as lakes. Zumberge (1952) defined a lake as an inland basin filled with water. Harding (1942) described lakes as "bodies of water filling depressions in the earth's surface."

LAKES AS NATURAL RESOURCES

The exact number of lakes in the United States is unknown. Welch (1952) estimated that there are at least 40,000 lakes in North America with a combined surface area of no less than 225,000 square miles (583,000 square kilometers). Hasler and Ingersoll (1968) reported a figure of 100,000 lakes in America (*i.e.*, United States).

Estimates of lake numbers from different sources or compiled at different times may exhibit wide disparity. The difference in estimates can be related to the lack of agreement as to what constitutes a lake, incompleteness of the inventories, and interpretational differences of maps and aerial photographs (Veatch and Humphrys, 1966). For example, Minnesota, "The Land of 10,000 Lakes," completed an inventory of its surface waters in 1968. The comprehensive final report initially defines a lake as "... an enclosed basin, filled or partially filled with water..." and then extends the term to include "...all natural enclosed depressions, 10 acres or more in area, which have substantial banks capable of containing water and which are discernable on aerial photographs." Minnesota has, according to the report, 15,291 lake basins of which 3,257 are partly or completely dry (Minnesota Department of Conservation, 1968).

Fresh-water lakes are really insignificant when compared to the earth's total surface as they account for about 0.16 percent of it (Table 4). Nace (1960) estimates that only about 0.009 percent cf the earth's total water supply is in the form of fresh-water lakes. In some regions lakes give the impression of dominating the landscape. Yet, in Beltrami County (Minnesota), a place renowned for its abundance of lakes, only about 18 percent of the area is under water (Minnesota Department of Conservation, 1968). Vilas County (Wisconsin), another governmental unit well endowed with lakes, has about 15 percent of its area covered by lakes (Deevey, 1942).

However, the geographic importance of any element of the landscape is not measured merely on the basis of its areal extent. The intrinsic properties of lakes make them a natural resource whose importance is greater than is suggested by area alone. Lakes are used as sources of municipal water, irrigation water, and cooling water for thermal-electric plants. They serve as transportation routes and as focal points for many types of recreational activity. Many lakes, particularly those in a pristine condition, are valued for their aesthetic qualities. They also provide convenient locations for dumping the organic and inorganic wastes of society.

An increasing number of lakes are viewed as merely obstacles in the "way of progress" and are being subjected to drainage or serving as land-fill sites to provide additional farmland or building sites. As the world's human population increases, it is likely that attempts to rid the landscape of lakes will increase in scope. Although drainage and land-fill schemes threaten some lakes, a problem of much greater magnitude is that of cultural (anthroprogenic) eutrophication.

LAKE SUCCESSION AND EUTROPHICATION

Lake Succession

Lakes, although giving the impression of permanence when measured on the scale of the human life span, are transitory features of the earth's surface. All lakes, regardless of their origin, pass through the process of ecological succession which ultimately results in a terrestrial environment. The ephemeral nature of lakes is a consequence of two fundamental processes, the downcutting of the outlet and, more important, the deposition of allochthonous and autochthonous materials in the basin.

Most lakes commence the successional process as bodies possessing relatively low concentrations of nutrients and, generally, low levels of

TABLE 4. DISTRIBUTION OF THE WORLD'S ESTIMATED WATER SUPPLY[a]

Location	Surface Area (km^2 x 10^3)	Volume of Water (km^3 x 10^3)	Percentage of Total Water
World	510,228		
Land Area	148,924		
Surface water on the continents			
Polar icecaps and glaciers	17,871	30,428	2.24
Fresh-water lakes	855	125	0.009
Saline lakes and inland seas	699	104	0.008
Average in stream channels		1	0.0001
Total surface water	19,425	30,658	2.26
Subsurface water on the continents			
Root zone of the soil	129,499	25	0.0018
Ground water above depth 805m		4,168	0.306
Ground water, depth of 805m to 4,024 m		4,168	0.306
Total subsurface water	129,499	8,361	0.61
World's oceans	361,303	1,321,314	97.1
Total water on land		39,014	2.87
Atmospheric moisture		12	0.001
Total, world supply of water		1,360,340	

[a] Adapted from Nace (1960).

productivity.* The importation and deposition of materials (e.g., sediment) from the shoreline and the surrounding watershed gradually decrease the lake depth. The addition of allochthonous materials normally enriches the water and thereby stimulates the production of organic materials. The autochthonous materials increase the sedimentation rate thus accelerating succession. Marked floral and faunal changes occur. Algal blooms become more common along with submergent and eventually emergent aquatic macrophytes. Desirable game fish may be replaced by less desirable species, the so-called "rough fish". A lake will eventually become a marsh or swamp which, in turn, terminates as dry land.

Lindeman (1942) stressed the productivity aspects in relation to lake succession. Figure 13 represents the probable successional productivity relationships for a hypothetical hydrosere developing from a moderately deep lake located in a fertile humid continental region. Productivity is initially low, a consequence of low nutrient levels, but increases rapidly as nutrients become more available. The length of time required for completion of the successional process is a function of several factors including lake basin morphology, climate, and the rate of influx and nutrient value of allochthonous materials. It is readily apparent that allochthonous nutrients can drastically increase lake productivity and thereby shorten the life span of a lake.

The Concept of Eutrophication

The word eutrophication, until recently foreign to the vocabulary of the general public, has appeared in the popular and scientific literature at a rapidly increasing rate over the past decade. The term is often used to denote the process whereby a pristine water body (e.g., lake) is transformed into one characterized by dense algal scums, obnoxious odors, and thick beds of aquatic macrophytes. However, the word is applied differently, according to the respective interests of its users.

Weber (1907) used the German adjectival form of eutrophication (nährstoffreichere - eutrophe) to describe the high concentration of elements requisite for initiating the floral sequence in German peat bogs (Hutchinson, 1973). The leaching of nutrients from the developing bog resulted in a condition of "mitterlreiche" (mesotrophe) and eventually "nährstoffearme" (oligotrophe). Naumann (1919) applied the words oligotrophic (under-fed), mesotrophic, and eutrophic (well-fed) to describe the nutrient levels (calcium, phosphorus, combined nitrogen) of water contained in springs, streams, lakes, and bogs (Hutchinson, 1973). Naumann (1931) defined eutrophication as the increase of nutritive substances, especially phosphorus and nitrogen, in a lake. Hasler (1947) broadly interpreted eutrophication as the "Enrichment of water, be it intentional or unintentional..." Fruh, et al. (1966) defined the word as the "enhancement of nutrients in natural water..." Edmondson (1974) suggested that many limnologists seem to use the term to describe "an increase in the rate of nutrient input..."

---

*Edmondson (1974) suggested that the idea, that all lakes are born oligotrophic and gradually become eutrophic as they age, is an old misconception.

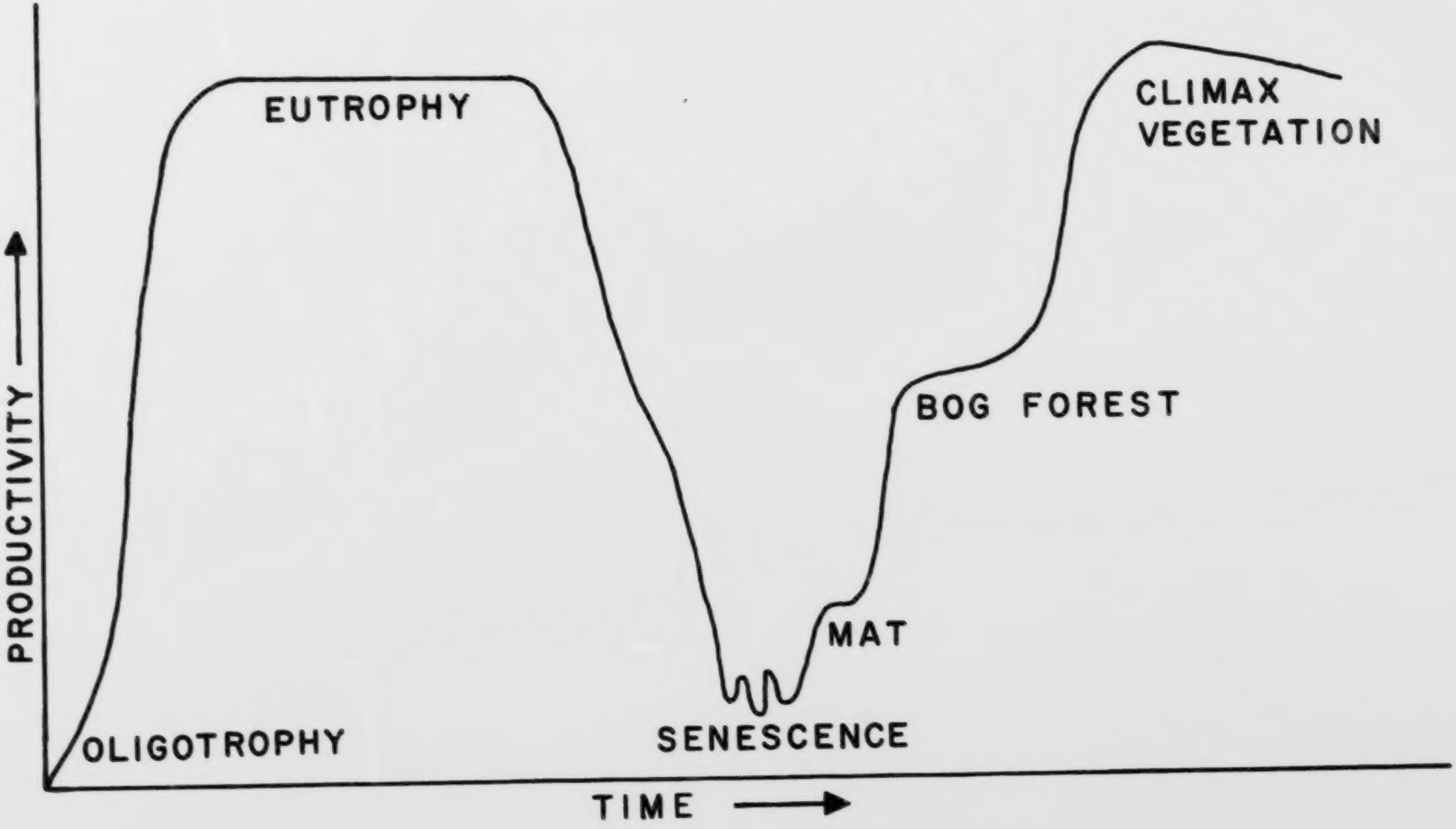


Figure 13. Hypothetical productivity growth-curve of a hydrosere.
Adapted from Lindeman (1942).

Hasler and Ingersoll (1968) suggested that eutrophication is the "process of enrichment and aging* undergone by bodies of fresh water". Vollenweider (1968) summarized the eutrophication of waters as meaning "... their enrichment in nutrients and the ensuing progressive deterioration* of their quality, especially lakes, due to the luxuriant growth of plants with its repercussions on the overall metabolism of the waters affected..."

A search of the literature on eutrophication indicates that the meaning of the term, originally limited to the concept of changing nutrient levels, has been gradually expanded to include the consequences of nutrient enrichment+.

Eutrophication occurs both naturally and as a result of man's activities (cultural or anthropogenic eutrophication). Many of man's practices relating to the disposition of municipal sewage and industrial wastes and land use impose relatively large nutrient loadings on many lakes and rivers. In many cases, the enrichment results in algal blooms and other symptoms of eutrophication. The consequences of man-induced eutrophication often make the water body less attractive to potential users. More importantly, at least when a long-range viewpoint is adopted, eutrophication accelerates lake succession, thus shortening the time period before a lake loses its identity.

Trophic State and Trophic Indicators

Limnologists and other scientists concerned with lakes have used the term "trophic state" (*i.e.*, degree of eutrophy) to describe two different lake characteristics, nutrient status and productivity. Thus, trophic state is a hybrid concept as suggested by Margalef (1958). Several different physical, biological, and chemical attributes are required to adequately describe a lake's trophic state, making the concept multidimensional (Brezonik and Shannon, 1971) and precluding its determination through direct measurement. However, it is possible to quantify trophic state through the use of trophic state indicators (indices) in conjunction with appropriate data reduction techniques.

There are numerous indicators of trophic state, each with its merits and shortcomings. Reviews have been written on the subject by Fruh, *et al.* (1966), Stewart and Rohlich (1967), Vollenweider (1968), and Hooper (1969). A list of some common indicators or indices are found in Table 5. A diversity of opinion exists regarding the number and kinds of indicators which should be considered in the classification of lakes. Use of a

---

* Emphasis added

+ The historical aspects and semantical problems associated with the word "eutrophication" and its companion words (oligotrophic, mesotrophic, eutrophic) are found in Weber (1907), Naumann (1919, 1931), Thienemann (1918), Rodhe (1969), Hutchinson (1967, 1973), Beeton and Edmondson (1972), and Edmondson (1974).

TABLE 5. TROPHIC INDICATORS AND THEIR RESPONSE TO INCREASED EUTROPHICATION[a]

Physical	Chemical	Biological
Transparency (d) (Secchi disc reading)	Nutrient concentrations (i) (*e.g.*, at spring maximum)	Algal Bloom frequency (i)
Morphometry (d)	Chlorophyll *a* (i)	Algal species diversity (d)
	Conductivity (i)	Littoral vegetation (i)
	Dissolved solids (i)	Zooplankton (i)
	Hypolimnetic oxygen deficit (i)	Fish (i)
	Epilimnetic oxygen supersaturation (i)	Bottom fauna (i)
	Sediment type	Bottom fauna diversity (d)
		Primary production (i)

[a] An (i) after an indicator signifies the value increases with eutrophication; a (d) signifies the value decreases with eutrophication. The biological indicators all have associated qualitative changes (*i.e.*, species changes occur as well as quantitative (biomass) changes as eutrophication proceeds). Adapted from Brezonik (1969).

single indicator has the virtue of simplicity but may produce misleading rankings or groupings because lakes are normally too complex to be adequately gauged on such a simplified basis. On the other hand, the use of a large number of indicators may result in a problem of character redundancy.

MULTIVARIATE CLASSIFICATION OF LAKES*

A multiplicity of classificatory schemes has been devised to group and rank lakes. Examples of some approaches to lake typology are found in: Lueschow, et al. (1970), Rawson (1956, 1960), Margalef (1958), Hansen (1962), Jarnefelt (1958), Larkin and Northcote (1958), Moyle (1945, 1946), Pennak (1958), Round (1958), Whipple (1898, Winner (1972), Zafar (1959), Beeton (1965), Donaldson (1969), and Gerd (1957). Hutchinson (1957, 1967) has reviewed many of the attempts to arrange lakes into orderly systems.

Lacustrine trophic state is a multi-dimensional concept and is, by its very nature, amenable to analysis by multivariate statistical techniques (e.g., cluster analysis, principal component analysis). Multivariate techniques minimize the personal bias often present when data are examined for groups, and rankings are developed. They are of particular value in situations where large numbers of objects or parameters are to be classified.

Numerical taxonomists and quantitative ecologists have been acutely aware of the benefits which can be derived from multivariate techniques and have been very active in promoting their use. Yet, a search of the literature has yielded few publications in which the techniques have been applied to lakes (e.g., Shannon, 1970; Brezonik and Shannon, 1971; Shannon and Brezonik, 1972a, 1972b; Sheldon, 1972). Shannon and Brezonik have devoted their efforts toward the classification and evaluation of 55 lakes in north central Florida. Sheldon reviewed the concept and functions of classification, introduced multivariate techniques of potential value in handling and synthesizing lake information, and applied the techniques to several lake populations.

Lake scientists have been slow to apply multivariate techniques to the problems of lake classification. This is probably because of a lack of familiarity with the techniques, the unavailability of large digital computers and/or the necessary software, and a shortage of comparable data from large numbers of lakes.

The balance of this section is devoted to the application of two multivariate techniques (cluster analysis, principal component analysis) to a group of 100 lakes (Table 3) using selected elements of ground truth collected by NES. The resulting multivariate trophic state index will be used in Section VI to assist in the assessment of LANDSAT-1 MSS as a tool in estimating the trophic status of lakes.

---

* The term classification is often used in the restricted sense of placing entities into distinct groups, thereby exluding arrangements showing no distinct divisions (e.g., ordination). The term is used here in the broader context suggested by Sneath and Sokal (1973).

Cluster Analysis

Cluster analysis is a collective term encompassing a broad spectrum of techniques for delineating natural groups ("clusters") of objects or attributes in hyperspace. A multitude of contributions have been published on the subject (e.g., Ward, 1963; Lance and Williams, 1967, 1968; Gower, 1967; Padron, 1969). Three comprehensive publications, written by Sokal and Sneath (1963), Anderberg (1973), and Sneath and Sokal (1973) serve as excellent sources of information. An exposé of the various clustering techniques available to researchers is beyond the scope of this investigation, and the reader is referred to the above sources.

Clustering on objects is termed Q-technique as opposed to R-technique which leads to classifications of attributes or characters (Sneath and Sokal, 1973). Williams and Dale (1965) suggested that, when the relationships are represented in hyperspace, the kind of space that is operated on should be called A-space and I-space, not R-space or Q-space. A-space (attribute space) has p dimensions, one for each attribute (character), in which there are n points, each representing an object. I-space (individual space) has n dimensions, one for each object, in which there are p points, each representing an attribute. This study will utilize the Q-technique operating in A-space.

Objects and Attributes

One hundred lakes, sampled by NES in 1972, were selected for analysis. Each lake was assigned a serial number (1-100) which is unique to this report. A careful examination of the physical, chemical, and biological parameters measured by NES resulted in the selection of six indicators for incorporation into both the cluster analysis and principal component analysis (PCA) ordination. A seventh indicator, an abbreviated form of the Pearsall cation ratio inverse was originally included, but was eliminated because it did not appear to contribute significantly to the classification scheme*.

The indicators (i.e., lake attributes) are: conductivity (COND, μmhos cm^{-1}), chlorophyll *a* (CHLA, $\mu g\ l^{-1}$), total phosphorus (TPHOS, mg l^{-1}), total organic nitrogen (TON, mg l^{-1}), algal assay yield (AAY, dry-wt in mg) and Secchi disc transparency (SECCHI, m). The inverse of Secchi disc transparency (ISEC, m^{-1}) was employed so that all of the indicator values would increase as trophic status increases.

The six indicators were selected because they are quantitative, considered to be important measures of trophic state, and satisfy Hooper's (1969) criteria for trophic indices. Annual mean values for COND, CHLA, TPHOS, and ISEC were used in the analyses; AAY and TON measurements were limited to the fall overturn sample, precluding the use of an annual mean. The descriptive statistics of the six indicators are found in Table 6. A serious lack of normality in the data necessitated a transformation prior to clustering. Natural logarithms (LN) were found to be adequate for this transformation.

---

* Abbreviated form of cation inverse is: ICAT = sodium / (calcium + magnesium).

Cluster Method

A complete linkage algorithm (McKeon, 1967) was used to examine the lakes for natural groupings. The method is also known as the furtherest neighbor hierarchical strategy (Lance and Williams, 1967) and the maximum method (Johnson, 1967). The algorithm is characterized as agglomerative, nonoverlapping, and hierarchical, the latter property permitting the output to be modelled in the form of dendrograms. The program was run on an International Business Machines (IBM) Model 370-155E digital computer at Optimum Systems Incorporated (OSI), Bethesda, Maryland.

The LN-transformed trophic indicator data were entered as an N x p matrix where N is the number of observations or objects (*i.e.*, lakes) and p is the number of dimensions or attributes (*i.e.*, indicators). The data points in each column (indicator) of the data matrix were standardized by subtracting the column mean from each point and then dividing by the column's standard deviation. This was accomplished using the McKeon program option number three. Standardization was necessary because the data were measured in different units.

Euclidian distance, an extension of the Pythagorean theorem to points in hyperspace, was selected as the similarity coefficient, largely because of its intuitive appeal. The formula for the Euclidian distance, Δ_{jk}, between two objects (*e.g.*, lake "j" and lake "k") is

$$\Delta_{jk} = \left[\sum_{i=1}^{p} (X_{ij} - X_{jk})^2 \right]^{\frac{1}{2}}$$

The distances between all possible (N(N-1)/2) pairs of objects are computed and stored in an N x N symmetrical matrix (S-matrix). The McKeon program uses the squared Euclidian distance, Δ^2, but the same clusters could be obtained by using Euclidian distance or any monotonic function of that distance.

The clustering procedure carries out successive iterations on the S-matrix which has the maximum squared distance within cluster in the diagonal and the maximum squared distance between clusters in the off-diagonals. Initially the S-matrix is N x N with zeros in the diagonals (Figure 14). At each

TABLE 6. DESCRIPTIVE STATISTICS OF 100 LAKES[a]

Statistic	CHLA (μg l^{-1})	ISEC (m^{-1})	COND (μmhos cm^{-1})	TPHOS (mg l^{-1})	TON (mg l^{-1})	AAY (mg dry-wt)
Mean	22.3	0.85	352	0.136	0.80	7.3
Median	11.8	0.54	353	0.048	0.67	2.7
Maximum value	381.2	5.37	808	1.893	3.35	61.3
Minimum value	1.1	0.13	50	0.005	0.08	0.1
Range	380.1	5.24	758	1.888	3.27	61.2
Standard deviation	42.7	0.88	155.9	0.265	0.56	10.6
Skewness	6.4	2.86	0.3	4.264	2.20	2.4

[a] The values above represent the statistics for the NES lakes which are incorporated into the cluster and principal component analyses.

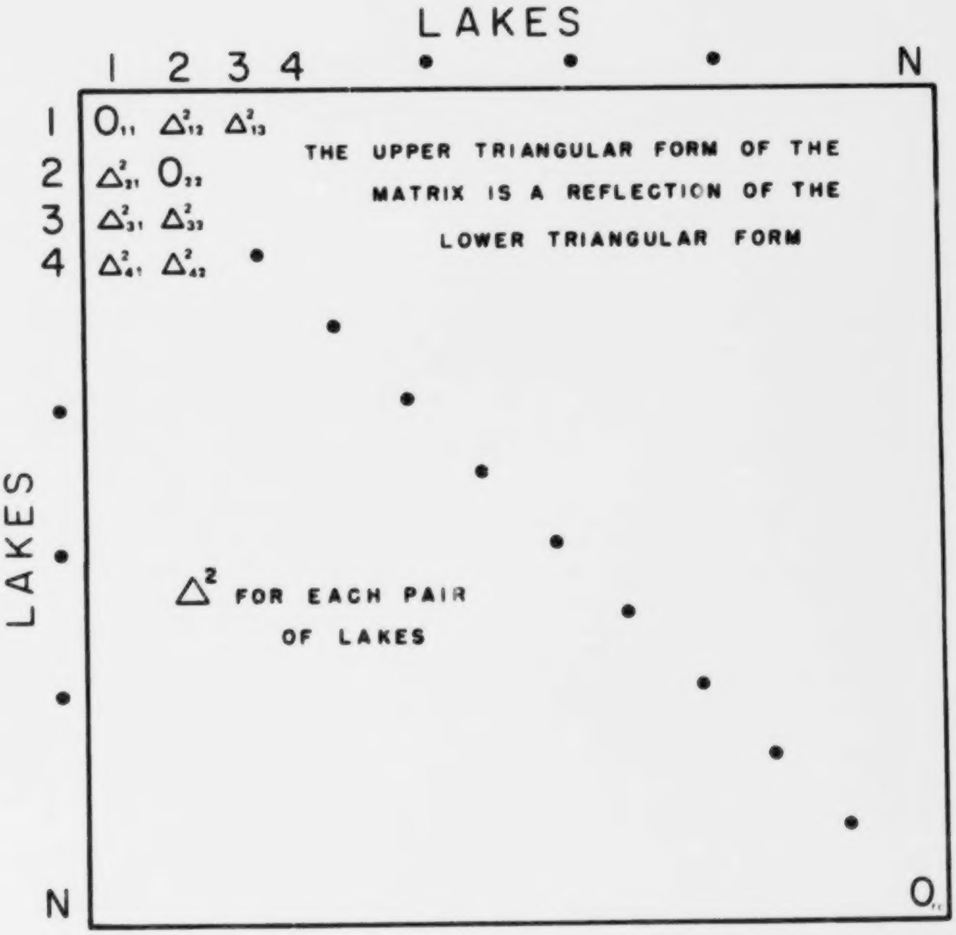

LAKES
1 2 3 4 • • • N
1
2
3
4
•
•
•
N
LAKES
0_{11} Δ^2_{12} Δ^2_{13}
Δ^2_{21} 0_{22}
Δ^2_{31} Δ^2_{32}
Δ^2_{41} Δ^2_{42}
THE UPPER TRIANGULAR FORM OF THE MATRIX IS A REFLECTION OF THE LOWER TRIANGULAR FORM
Δ^2 FOR EACH PAIR OF LAKES
0_{nn}

Figure 14. N x N S-matrix. Initially the matrix has only zeros on the diagonal. The off-diagonal elements represent the squared Euclidian distances between each pair of lakes. There are 4,950 distances possible for 100 lakes. Appendix E contains the matrix of Δ^2 used to examine the NES-sampled lakes for clusters.

iteration, those two clusters are combined, which, taken together, form the most compact cluster. The measure of compactness is the maximum distance between any two points (i.e., lakes) within the cluster. The next pair to be combined are identified by finding the smallest squared distance between points in the off-diagonals.

For example, if N=100, the program will start out with 100 clusters and successively meld the clusters, two per iteration, eventually terminating with one cluster containing 100 objects.

Results and Discussion

The results of the cluster analysis are depicted as a dendrogram (Figure 15). The abscissa is scaled in Euclidian distance with the points of junction between stems implying that the maximum within-cluster distance is the value on the abscissa. Generally, the ordinate of a dendrogram has no special significance. The order of the clusters can be changed by rotating the stems, thereby producing a multitude of apparently different dendrograms. Interpretational problems arise when it is necessary to compare dendrograms developed from different data or algorithms.

Some investigators attempt to "standardize" the ordinate-induced appearance of the dendrogram by rotating the stems to keep the code or serial numbers as ordered as possible, especially if the numbers present linear arrangements of generally established taxonomic groups (Sneath and Sokal, 1973). The author has attempted to order the axis by rotating the stems to reflect the PCA ordination results found in the next section of this chapter. Consequently, the trophic status of the 100 lakes in the dendrogram generally increases along the ordinate in the "downward" direction.

It has become an accepted practice in lake studies to use the terms oligotrophic, mesotrophic, and eutrophic in reference to the trophic status of lakes. The terms, although well established in the literature, are used freely and it is difficult to quantitatively determine what is meant by them (Beeton, 1965). It may be argued that the terms serve to stereotype lakes and unduly restrict, to three categories, what may be members of a trophic continuum. However, this terminology is likely to continue in vogue because, at a very minimum, it gives some indication of trophic state.

The question arises regarding the number of "good" natural clusters which have been depicted by the clustering algorithm. McKeon (1967) asserted that a sudden increase in the maximum within cluster distance suggests that the previous stage may be a good stopping point. The first "sudden" increase occurs between Δ3.70 and Δ4.35 indicating that there may be seven relatively coherent clusters (A, B, C, D, E, F, G). There is some difficulty involved in reconciling the seven clusters with the three classic states.

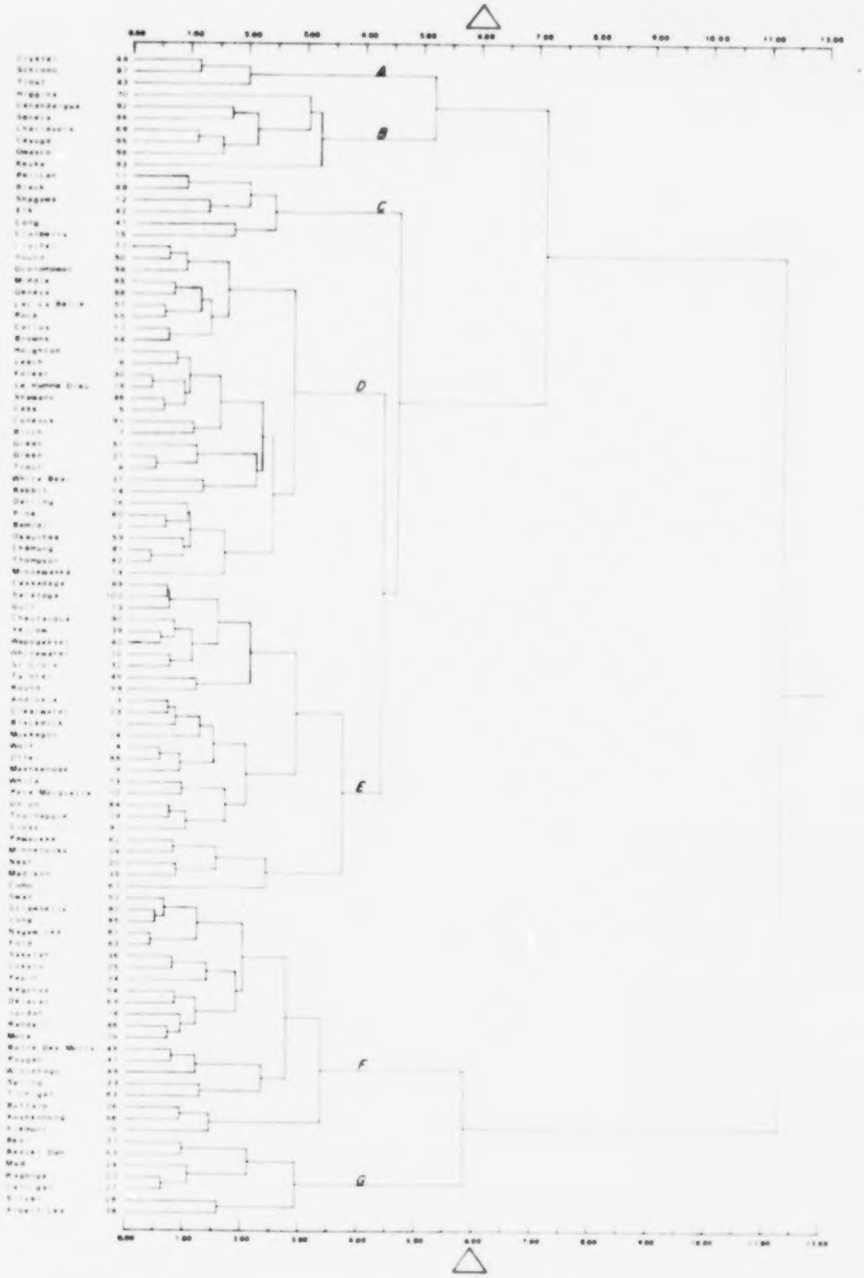


Figure 15. Dendrogram of 100 lakes sampled by the National Eutrophication Survey during 1972. The dendrogram is based on a complete linkage algorithm using generalized Euclidian distance as the measure of similarity.

The NES, cognizant of the advantages and limitations of naming lakes according to a three-class trophic scheme, has applied the trophic names to these lakes using data collected in 1972 and information acquired from various sources, including reports and knowledgeable individuals. Using the NES assessments as a guide, Clusters A and B may be characterized as containing a mixture of oligotrophic and mesotrophic lakes. Cluster C consists of eutrophic lakes; Cluster D is comprised of both mesotrophic and eutrophic lakes. Eutrophic lakes made up Clusters E and F. Cluster G consists of lakes which are very eutrophic (hypereutrophic).

The results of the cluster analysis appear distressing in light of the three-class concept of trophic state. A more careful selection of candidate lakes could have resulted in the "discovery" of three groups matching the classic trophic states. Nevertheless, the clustering approach is of value in showing relationships among lakes. It gives the investigator another way of perceiving his study lakes, and it is hoped will enable him to see more clearly the relationships between large numbers of lakes.

Principal Components Ordination

Hierarchical methods are a rather heavy-handed approach to the problem of reducing the dimensionality of multidimensional systems (Sheldon, 1972). They have the inherent capability to yield some form of clusters regardless of the structure of the data constellation, even if the entities to be analyzed are randomly distributed (Sneath and Sokal, 1973). Another approach that merits consideration is ordination. Ordination is the placement of N entities in A-space varying in dimensionality from 1 to p or N-1, whichever is less. Principal components analysis, one ordination technique, will be used to examine the lakes in A-space for natural clusters and to derive a multivariate trophic state index.

Principal components analysis may be used to reduce the dimensionality of a multivariate system by representing the original attributes as functions of the attributes. The main object is to summarize most of the variance in the system with a lesser number of "artificial" variates (*i.e.*, principal components).

The computation of principal components can be undertaken using either a covariance matrix (S) or a p x p matrix of Pearson product-moment correlation coefficients (R). Use of the R-matrix is indicated when the variates are measured in different units (*e.g.*, grams and meters). Computation of the R-matrix principal components involves the extraction of its eigenvalues (characteristic or latent roots) and eigenvectors (characteristic or latent vectors). The eigenvalues are a set of r nonzero, positive scalar quantities. The sum of the R-matrix eigenvalues is the matrix trace and is equal to the number of dimensions in the original system (*i.e.*, the number of variates, p). The rank of the matrix is r and is equal to p.

Normalized eigenvectors give the A-space coordinates of an orthogonal set of axes known as the principal axes. The normalized eigenvectors are commonly designated as principal components.

The first principal component of the observations of the p-variates $X_1, \ldots, X_p$ is the linear compound

$$Y_1=a_{11}\ X_1 + \ldots + a_{p1}\ X_p$$

whose coefficients (a_{i1}) are the elements of the eigenvector associated with the largest eigenvalue of the R-matrix (Morrison, 1967). The variance of the first principal component is associated with the eigenvalue. The jth principal component of the p-variate system is the linear compound

$$Y_j=a_{1j}X_1 + \ldots + a_{pj}\ X_p$$

whose coefficients are the elements of the eigenvector associated with the jth largest eigenvalue extracted from the R-matrix. The jth eigenvalue is a measure of the variance of the jth principal component.

The proportion of the total sample variance in the cloud of dimensionless standard scores attributable to any component is found by dividing its eigenvalue by p. The first principal component has the innate property of explaining the greatest proportion of the sample variance with each successive component explaining progressively smaller amounts of the total sample variance. Frequently, a consequence of the decreasing order of variance, $k < r$ dimensions will adequately summarize the variability of the original variates $X_1, \ldots, X_p$. The first three components generally account for most of the variation permitting the ordination of the subjects in 1-D, 2-D, and 3-D space. All of the dispersion in the data can be accounted for by using r dimensions, but this negates the analysis objective, the reduction of dimensionality or as Seal (1964) stated the "... parsimonious summarization of a mass of observations."

The principal components of N p-variate observations may be defined geometrically (Morrison, 1967) as "... the new variates specified by the axes of a rigid rotation of the original response coordinate system into an orientation corresponding to the directions of maximum variance in the sample scatter configuration." The normalized eigenvectors give the directions of the new orthogonal axes and the eigenvalues determine the lengths (*i.e.*, variance) of their respective axes. The coordinate system is expressed in standard units (zero mean, unit variances) when the components are extracted from the R-matrix. Figure 16 is a hypothetical bivariate example of the geometric meaning of principal components.

Detailed descriptions of the theoretical and computational aspects of principal components are found in Hotelling (1933a, 1933b, 1936), Anderson (1958), and Morrison (1967).

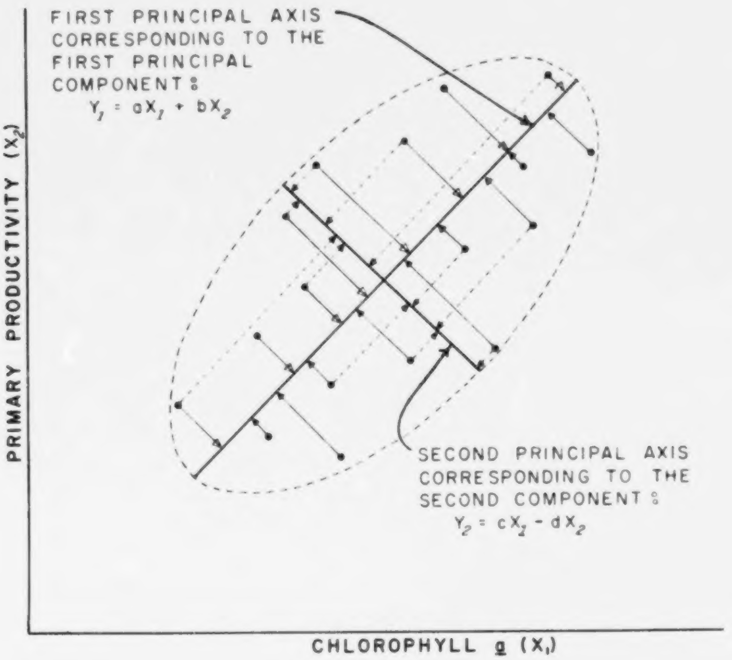

FIRST PRINCIPAL AXIS CORRESPONDING TO THE FIRST PRINCIPAL COMPONENT:
$Y_1 = aX_1 + bX_2$
SECOND PRINCIPAL AXIS CORRESPONDING TO THE SECOND COMPONENT:
$Y_2 = cX_1 - dX_2$
PRIMARY PRODUCTIVITY (X_2)
CHLOROPHYLL a (X_1)

Figure 16. Geometrical interpretation of the principal components for a hypothetical bivariate system. Principal components may be interpreted geometrically as the variates corresponding to the orthogonal principal axes of observation scatter in A-space. The elements of the first normalized eigenvector (i.e., coefficients of the first principal component) define the axis which passes through the direction of maximum variance in the scatter of observations. The associated eigenvalue corresponds to the length of the first principal axis and estimates the dispersion along it. The second principal component corresponds to the second principal axis, the length of which represents the maximum variance in that direction. In our example the first component accounts for most of the dispersion in the data swarm and the original 2-dimensional system could be summarized in one dimension with little loss of information. The new variate value (PC1) for each lake is obtained by evaluating the first component

$$Y_1 = aX_1 + bX_2$$

The PC1 for each lake in 1-D A-space is its coordinate on the first component axis and is shown diagrammatically by projecting each observation to the principal axis. (Modified from Brezonik and Shannon, 1971).

Methodology

The principal components analysis was accomplished using the same 100 lakes and LN-transformed trophic state indicator data used in the hierarchical cluster analysis (LNCHLA, LNISEC, LNCOND, LNTPHOS, LNTON, LNAAY). The data matrix was further standardized (zero mean, unit variance) by attributes using the relationship

$$z_{ij} = (X_{ij} - \bar{X}_i)/s_i$$

where z_{ij} is the standardized values for attribute i of observation (*i.e.*, lake) j; X_{ij} is the LN-transformed value of observation j; and $\bar{X}_i$ and s_i are the mean and standard deviation of attribute j, respectively.

The eigenvectors and eigenvalues were extracted from a p x p correlation matrix (Table 7). All of the computational aspects were executed on a Control Data Corporation digital computer (CDC 3300) at Oregon State University using the Statistical Interactive Programming System (SIPS). A detailed explanation of SIPS, and its operation is found in Guthrie, Avery, and Avery (1973).

TABLE 7. R-MODE CORRELATION MATRIX OF SIX TROPHIC STATE INDICATORS. The coefficients were determined using LN-transformed data for the 100 NES-sampled lakes.

	LNCHLA	LNISEC	LNCOND	LNTPHOS	LNTON	LNAAY
LNCHLA	1.000	0.886	0.397	0.801	0.684	0.686
LNISEC		1.000	0.285	0.777	0.660	0.597
LNCOND			1.000	0.397	0.378	0.327
LNTPHOS				1.000	0.683	0.810
LNTON					1.000	0.576
LNAAY						1.000

As was asserted earlier, principal components analysis can be used to advantage because often $k \leq 3$ dimensions will explain most of the variance in the hyper-dimensional cloud of data points. The resulting ordinations can be expressed as 1-D, 2-D, and 3-D models. The ordinations are usually expressed as a sequential numerical listing (*i.e.*, 1-D model), a scatter diagram (*i.e.*, a 2-D model), or as a set of three 2-D scatter diagrams which, when examined carefully, may give some indication of the scatter of observations in an A-space of three dimensions. However, unless the pattern of diversity is simple, it is rather difficult for most individuals to visualize the pattern in 3-D space using a series of 2-D projections. Fraser and Kovats (1966) and Rohlf (1968) have advocated the use of stereographic projections for ordination in 3-space and have furnished the equations necessary for the development of stereoscopic models (i.e., stereograms). Some examples are found in Schnell (1970), Moss (1967), and Sneath and Sokal (1973).

This investigator has employed the techniques in Rohlf (1968) to construct 3-dimensional ordination models by plotting the lakes in the 3-D space produced by the first three principal components. The models can be examined visually for the presence of clusters. Unlike the clustering approach, no assumptions are made that the lakes must congregate into a series of clusters.

The model, as used here, consists of one member of a stereo pair; the other member is easily produced if the complexity of the data necessitates the advantages inherent in viewing the objects in stereo. The lake coordinates, determined by evaluating the three components for each lake, are standardized to make the scale for the longest axis (X) run from 0.0 to 1.0. The other axes are scaled-down proportionally. The component with the smallest range is assigned to the vertical (Z) axis. The models were plotted on a Calcomp (IBM-1724) 30 inch incremental drum plotter driven by the Oregon State University CDC 3300 computer using subroutines found in GRAFPAC, a plotting routine package developed by Rohlf (1968). The same modelling approach is used in Section VII to depict LANDSAT-1 MSS color ratio relationships.

Results and Discussion

The normalized eigenvectors and eigenvalues are found in Table 8. Although the principal component analysis is of value in reducing the dimensionality of a multivariate system, it is sometimes difficult to interpret the new variates in terms of subject matter identities. Some indication of a principal component's meaning may be ascertained by an examination of the algebraic sign and magnitude of its coefficients.

The coefficients of the first component (Table 8), excluding the coefficient for LNCOND, are nearly equal in magnitude suggesting that it represents a general measure of trophic state, accounting for approximately 68 percent of the variation in the data. Correlations between the new variate and the LN-transformed trophic indicators are found in Table 9.

The first principal component was evaluated for each of the 100 lakes. The resultant values (PC1) are indicative of each lake's respective position on a multivariate trophic scale (Table 10). The procedure followed is essentially that of Brezonik and Shannon (1971), but the

TABLE 8. NORMALIZED EIGENVECTORS AND EIGENVALUES[a]

Eigenvector Number	LNCHLA	LNISEC	LNCOND	LNTPHOS	LNTON	LNAAY	Eigenvalue	Variance (%)	Cumulative Variance (%)
1	0.457	0.435	0.251	0.458	0.403	0.408	4.081	68.02	68.02
2	-0.112	-0.249	0.952	-0.088	0.010	-0.104	0.810	13.50	81.52
3	-0.222	-0.397	-0.018	0.271	-0.383	0.757	0.477	7.95	89.47
4	-0.346	-0.395	-0.143	-0.040	0.829	0.122	0.387	6.45	96.92
5	-0.436	0.060	-0.006	0.797	-0.056	-0.410	0.152	2.54	98.46
6	-0.647	0.657	-0.099	-0.270	0.008	0.258	0.092	1.54	100.00
							5.999	100.00	

---

[a] The principal components analysis was performed using an R-matrix of correlation coefficients for six trophic state indicators. The data represent 100 lakes sampled by NES during 1972.

scale was not shifted into the positive domain by correcting each lake's PC1 with the PC1 obtained from a hypothetical lake. The lake lying at the negative end of the scale, Crystal Lake, is rated as having the lowest trophic status of those studied; in other words, it has relatively high water quality. Trophic state increases in the positive direction on the scale with the lake lying at the positive extreme, Albert Lea Lake, exhibiting the highest trophic state of the 100 lakes studied. Some breaks or gaps are evident on the scale, but only toward the two extremes. A very discernible gap occurs between Beaver Dam Lake (53, position 95) and Mud Lake (24, position 96); the Mud Lake - Albert Lea Lake group might be termed as hypereutrophic.

TABLE 9. PRODUCT-MOMENT CORRELATION COEFFICIENTS OF THE TROPHIC STATE INDICATORS AND THE PRINCIPAL COMPONENTS.

	Principal Component					
	1	2	3	4	5	6
LNCHLA	0.92	-0.10	-0.15	-0.22	-0.17	-0.20
LNISEC	0.88	-0.22	-0.27	-0.25	0.02	0.20
LNCOND	0.51	0.86	-0.01	-0.09	-0.20	0.01
LNTPHOS	0.92	-0.08	0.19	-0.03	0.31	-0.08
LNTON	0.82	0.01	-0.26	0.52	-0.02	0.00
LNAAY	0.83	-0.09	0.52	0.08	-0.16	0.08

The magnitude of the first component's coordinates suggests that a less elegant approach toward an ordination of the lakes might be undertaken with similar results. The approach, using the same LN-transformed standardized indicator values, involves the summation of a lake's indicator values and then dividing by p, the number of indicators. In other words

$$MCR_j = (X_{j1} + \ldots + X_{jp}) / P_j$$

where MCR_j is the Mean Composite Rank for the jth lake, X_{j1} is the jth lake's score on the first trophic indicator, X_{jp} is the lake's score on the pth indicator and p is the number of dimensions or indicators. The results of this ranking method are found in Table 10 along with the principal components ordination. The two methods of ordinating the lakes are in close agreement. However, the principal component approach has the advantage of permitting the development of 2-dimensional and 3-dimensional ordinations which explain a very high percentage of the variance.

TABLE 10. PRINCIPAL COMPONENT ORDINATION AND MEAN COMPOSITE RANK ORDINATION OF 100 LAKES

Position	Lake Name	Serial Number	PC1 Value	Lake Name	Serial Number	MCR Value
1	Crystal	44	-5.04	Crystal	44	-2.17
2	Schroon	87	-4.59	Schroon	87	-1.99
3	Higgins	70	-3.92	Higgins	70	-1.56
4	Canandaigua	92	-3.63	Canandaigua	92	-1.42
5	Charlevoix	69	-3.60	Charlevoix	69	-1.41
6	Trout	43	-3.24	Trout	43	-1.39
7	Seneca	94	-2.89	Seneca	94	-1.03
8	Cayuga	95	-2.74	Cayuga	95	-1.02
9	Crystal	77	-2.52	Owasco	96	-0.98
10	Owasco	96	-2.47	Crystal	77	-0.95
11	Middle	65	-2.29	Middle	65	-0.85
12	Keuka	93	-2.14	Keuka	93	-0.85
13	Round	50	-2.09	Round	50	-0.79
14	Oconomowoc	58	-1.82	Houghton	71	-0.66
15	Geneva	68	-1.71	Pelican	11	-0.65
16	Green	51	-1.67	Oconomowoc	58	-0.64
17	Houghton	71	-1.61	Geneva	68	-0163
18	Carlos	17	-1.55	Green	51	-0.62
19	Lac La Belle	57	-1.43	Long	41	-0.59
20	Leech	6	-1.43	Birch	7	-0.58
21	Conesus	91	-1.41	Leech	6	-0.57
22	White Bear	31	-1.41	Carlos	17	-0.57
23	Birch	7	-1.39	White Bear	31	-0.55
24	Pelican	11	-1.27	Conesus	91	-0.54
25	Forest	30	-1.22	Lac La Belle	57	-0.51
26	Rock	55	-1.21	Forest	30	-0.49

TABLE 10. PRINCIPAL COMPONENT ORDINATION AND MEAN COMPOSITE RANK ORDINATION OF 100 LAKES (continued)

Position	Lake Name	Serial Number	PC1 Value	Lake Name	Serial Number	MCR Value
27	Green	21	-1.10	Cassadaga	89	-0.50
28	Long	41	-1.07	Rock	55	-0.44
29	Browns	64	-1.07	Black	88	-0.42
30	Le Homme Dieu	18	-1.06	Le Homme Dieu	18	-0.41
31	Cassadaga	89	-1.04	Green	21	-0.41
32	Trout	8	-1.01	Shagawa	12	-0.40
33	Shawano	46	-0.94	Shawano	46	-0.40
34	Cass	5	-0.90	Trout	8	-0.38
35	Black	88	-0.77	Cass	5	-0.36
37	Darling	16	-0.73	Gull	13	-0.34
38	Pine	60	-0.71	Chautauqua	90	-0.34
39	Chautauqua	90	-0.66	Cranberry	15	- 30
40	Okauchee	59	-0.62	Pine	60	26
41	Shagawa	12	-0.58	Saratoga	100	.25
42	Saratoga	100	-0.57	Darling	16	.24
43	White	73	-0.47	Whitewater	10	-0.24
44	Rabbit	14	-0.46	Elk	42	-0.22
45	Bemidji	2	-0.44	Okauchee	59	-0.18
46	Cranberry	15	-0.40	Rabbit	14	-0.17
47	Whitewater	10	-0.38	Yellow	39	-0.17
48	Minnewaska	19	-0.32	Bemidji	2	-0.16
49	Andrusia	3	-0.24	St. Croix	32	-0.14
50	Yellow	39	-0.23	White	73	-0.13
51	Pere Marquette	72	-0.21	Wapogasset	40	-0.12
52	St. Croix	32	-0.17	Andrusia	3	-0.11

TABLE 10. PRINCIPAL COMPONENT ORDINATION AND MEAN COMPOSITE RANK ORDINATION OF 100 LAKES (continued)

Position	Lake Name	Serial Number	PC1 Value	Lake Name	Serial Number	MCR Value
53	Wapogasset	40	-0.16	Pere Marquette	72	-0.04
54	Elk	42	-0.08	Minnewaska	19	-0.03
55	Chemung	81	-0.06	Blackduck	1	-0.02
56	Blackduck	1	0.01	Chemung	81	0.02
57	Clearwater	23	0.01	Wolf	4	0.02
58	Thompson	82	0.03	Otter	98	0.03
59	Wolf	4	0.11	Clearwater	23	0.03
60	Otter	98	0.13	Thompson	82	0.08
61	Muskegon	74	0.18	Muskegon	74	0.09
62	Union	84	0.43	Tainter	45	0.10
63	Tainter	45	0.44	Union	84	0.22
64	Thornapple	79	0.58	Mashkenode	9	0.27
65	Pewaukee	62	0.59	Pewaukee	62	0.29
66	Swan	52	0.68	Swan	52	0.30
67	Minnetonka	29	0.73	Minnetonka	29	0.30
68	Maskenode	9	0.74	Thornapple	79	0.30
69	Nest	20	0.77	Nest	20	0.32
70	Cross	97	0.86	Round	99	0.37
71	Strawberry	80	0.99	Cross	97	0.41
72	Round	99	1.02	Strawberry	80	0.45
73	Long	85	1.14	Como	67	0.46
74	Como	67	1.15	Butte des Morts	48	0.48
75	Butte des Morts	48	1.27	Long	85	0.50
76	Nagawicka	61	1.27	Madison	35	0.53
77	Ford	83	1.36	Nagawicka	61	0.56
78	Madison	35	1.36	Sakatah	36	0.57

TABLE 10. PRINCIPAL COMPONENT ORDINATION AND MEAN COMPOSITE RANK ORDINATION OF 100 LAKES (continued)

Position	Lake Name	Serial Number	PC1 Value	Lake Name	Serial Number	MCR Value
79	Sakatah	36	1.38	Jordan	78	0.58
80	Jordan	78	1.41	Kegonsa	54	0.59
81	Kegonsa	54	1.48	Ford	83	0.60
82	Cokato	25	1.61	Poygan	47	0.65
83	Poygan	47	1.68	Cokato	25	0.71
84	Randall	86	1.92	Randall	86	0.80
85	Delavan	66	2.03	Delavan	66	0.83
86	Pepin	34	2.10	Pepin	34	0.86
87	Mona	76	2.17	Mona	76	0.87
88	Buffalo	26	2.31	Winnebago	49	0.91
89	Spring	33	2.33	Buffalo	26	0.92
90	Winnebago	49	2.36	Spring	33	0.94
91	Koshkonong	56	2.45	Koshkonong	56	1.02
92	Fremont	75	3.06	Bear	37	1.25
93	Tichigan	63	3.11	Fremont	75	1.25
94	Bear	37	3.15	Tichigan	63	1.27
95	Beaver Dam	53	3.29	Beaver Dam	53	1.29
96	Mud (at Maple Lake)	24	4.32	Mud (at Maple Lake)	24	1.70
97	Wagonga	22	4.40	Carrigan	27	1.76
98	Carrigan	27	4.40	Wagonga	22	1.79
99	Silver	28	4.79	Silver	28	1.89
100	Albert Lea	38	5.90	Albert Lea	38	2.34

The second component (Table 8) explains about 14 percent of the variation in the data. The LNCOND coordinate of the component is very large suggesting that the second variate is largely a measure of conductivity. The second component has a good correlation with LNCOND (Table 9).

The third component (Table 8) accounts for approximately 8 percent of the variance. LNAAY is the trophic indicator which shows the strongest correlation with the third component (Table 9), but is not readily interpretable.

Approximately 89 percent of the total sample variance can be attributed to the first three components. Figure 17 depicts the 100 lakes ordinated in 3-D space defined by the first three components. Some small clusters are apparent, but they are not well defined. The long axis is the first principal component axis (I). The axis labelled II is the second component and the vertical axis (III) is the third component.

The failure to discern well defined clusters may be partially a consequence of the trophic state of the lakes incorporated into this analysis; the NES lake population is heavily weighted toward lakes having water quality problems.

Summary

One hundred lakes were subjected to two complementary multivariate analyses, a complete linkage hierarchical cluster analysis and ordination using the technique of principal components. Well-defined clusters or natural groupings were not found through either approach. This may be a consequence, at least partially, of the "kinds" of lakes incorporated into the analyses.

The first principal component was evaluated for each lake and the resulting value (PC1), its coordinate on the axis, used as a multivariate index of the lake's trophic state. The PC1's are purported to represent an assessment of lacustrine trophic state and will be used in Section VII to evaluate LANDSAT-1 MSS color - lake relationships.

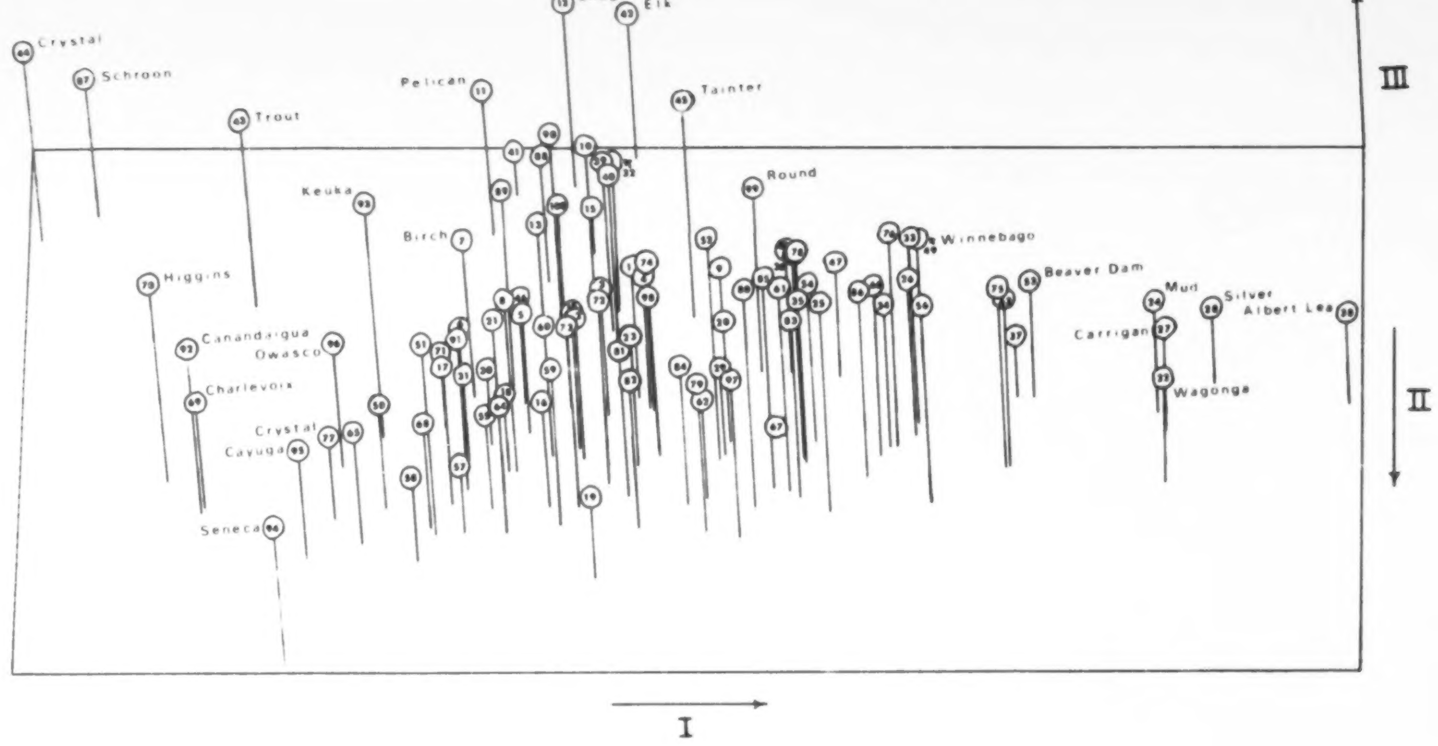


Figure 17. The three-dimensional principal component ordination of 100 lakes sampled by the National Eutrophication Survey during 1972.

SECTION V

LANDSAT-1 DATA EXTRACTION TECHNIQUES AND PRODUCTS

LANDSAT-1 MSS data are available from EROS in the form of photographic products and computer-compatible digital magnetic tapes (CCT's). The data forms permit investigators two general approaches to the problem of data extraction and utilization, the photographic approach and the CCT approach. Each has its particular advantages and limitations.

MSS DATA EXTRACTION APPROACHES

Photographic Approach

The photographic products available from EROS include black and white (b&w) negative and positive transparencies, and prints. False color prints and transparencies are available for a very limited number of scenes. All are either third or fourth generation photographic products. The photographs may be examined visually, as was done in Section III, for differences in gray tone, texture, shape, size, and pattern. Techniques common to the interpretation of aerial photographs may be employed to extract information pertinent to many different fields of science.

Quantification of the information contained in the undodged photographic products may be achieved through microdensitometry and photographic techniques including false color enhancement and density slicing. Manual and automatic microdensitometry can be used to digitize the information contained on the photographic positive or negative transparencies. This is easily accomplished with a microdensitometer by directing a light beam of known intensity through a small segment (e.g., lake image or portion of a lake image) of the transparency and measuring any changes in intensity on a numerical scale as percent transmission or as optical density. The quantitative data may then be used to examine correlations between MSS bands and lake indicators relating to trophic state.

Automatic scanning systems permit density slicing, the separation of the different densities on a transparency and their coding for later reproduction as b&w and color-enhanced products or symbolized listings. Reliance upon sophisticated instrumentation for the determination of areas of equal density (i.e., equidensities) can be avoided by using various photographic enhancement techniques. Nielsen (1972) summarizes a simple process reported by Ranz and Schneider (1970) which utilizes Agfacontour film for the production of equidensities.

The photographic approach is attractive because it can be accomplished with relatively simple equipment (unless a fully automated scanner is used) and is inexpensive. The four transparencies required to give all band (green, red, IR1, IR2) coverage of a LANDSAT-1 MSS scene cost only ten percent of the listed (November 1975) EROS price for a comparable set of CCT's ($20.00/$200.00). Many investigators, lacking the necessary computer and software for processing the CCT's, are able to explore possible applications of LANDSAT-1 data in their areas of specialization using the photographic approach.

However, the approach has several limitations which are particularly serious in water resources studies and which merit mention. The transparencies have a relatively small density range when compared to the sensitivity range of the MSS; this results in a scale compression when the MSS data are transformed into a film image on an electron beam recorder (EBR). The range of energy returns from water bodies is small and located at the lower end of the MSS intensity scale. Compression of the overall scale increases the difficulty of discriminating differences in water quality.

As mentioned previously, the photographic materials are third and fourth generation products (the first generation is the film image produced by the EBR), and the errors common to photographic processing are compounded. Chemical adjacency effects and the nonlinearity of the density-log exposure (D-log E) curve increase the magnitude of the problem. An additional element of uncertainty is introduced by the microdensitometer.

This investigator is not trying to assert that the photographic approach is totally lacking in merit, but rather that its limitations seriously limit the investigator attempting a quantitative estimation of lake parameters relating to trophic indicators and trophic state.

CCT Approach

The use of computer compatible tapes to study LANDSAT-1 MSS sensed phenomena is not only more expensive, but it is also more restrictive because there are relatively few research centers with the requisite computer software and output devices to use the digital data to full advantage. However, these limitations are overshadowed by the fact that the tapes contain, in digital form, the actual data point values recorded by the MSS. Investigators can avoid the numerous uncertainties introduced when the original MSS data are coded by an electron beam recorder (EBR) into photographic forms and then re-quantified through microdensitometry.

This investigation was initiated using the photographic approach. A manually operated microdensitometer was used to measure the optical density (OD) of lake images. Differences in OD were detected, but several difficulties were encountered (e.g., variation in the quality of the transparencies, locating the lakes on the green band transparencies), and the approach was abandoned in favor of the CCT approach.

The CCT approach permits the rapid determination of picture element (pixel) counts, descriptive statistics (e.g., means, standard deviations, and histograms), density slicing, and affords the opportunity to enhance optional photographic products through both linear and non-linear contrast stretching.

The utilization of CCT's is not without its problems, most of which are related to the quality of the information contained on the tapes. Defects commonly contained in the MSS data recorded on the tapes include missing lines and random bit-dropout for major portions of lines. The defective tapes can be repaired using existing software, but at additional cost both in time and money. Another problem is the receipt of CCT's not meeting the specification of the purchase order (e.g., receipt of 9-track instead of 7-track tapes; 556 bpi instead of 800 bpi tapes). While this is a minor problem, it does cost the investigator valuable time.

CCT DATA EXTRACTION TECHNIQUES

The LANDSAT-1 MSS CCT's used in this investigation were processed at the Image Processing Laboratory (IPL), a support facility of the Jet Propulsion Laboratory (JPL), California Institute of Technology. In this section, the author will briefly discuss the image processing system and, using one lake as an example, outline the data extraction techniques employed.

Image Processing System

The IPL system consists of an IBM 360/44 computer with five tape drives, four disc drives, a quick-look Polaroid pictorial output device, and a core-refreshed interactive display (Blackwell and Boland, 1974). A video film converter (VFC) provides offline hardcopy pictorial input and output capabilities. This device has a precision cathode ray tube (CRT), and 70-mm and 35-mm cameras. In the pictorial output mode, the VFC reads a digital magnetic tape, containing a digital image, and displays that image on the CRT, exposing the film which is then developed and printed, producing a hardcopy output of the digital image. In the pictorial input mode, the VFC functions as a flying spot scanner producing a digital output picture on magnetic tape.

The IPL IBM 360/44 operates under the control of a special software system, VICAR (Video Information Communication and Retrieval). Presently, a highly stylized Operating System (OS) is operational which permits foreground-background, roll-in and roll-out capabilities. VICAR is designed to allow very flexible manipulation of digital pictures consisting of rectangular arrays of optical measurements. The system contains a library of more than two hundred operationally executable image-processing programs. Each program operates on an input digital picture stored on magnetic tape or disc. Processing line-by-line, it generates an output picture on tape or disc, preserving the input data. Additional information regarding the system and existing programs is found in Frieden (1971), Anon (1973), and Blackwell and Billingsley (1973).

Data Extraction Technique

LANDSAT-1 MSS Frame 1017-16093 and one of its lakes, Lake Koshkonong (56), will be used to illustrate the methodology used to extract the digital information contained in a set of CCT's.

The extraction process commences with a change in the format of the Goddard Space Flight Center (GSFC) CCT's and an expansion to 8-bit mode giving a total of 256 digital number (DN) levels (0 to 255) of optical intensity. The system is capable of handling the data contained on two CCT's at a time, resulting in an initial output consisting of one half of an LANDSAT-1 frame. An example of the left half of Frame 1017-16903 is shown in Figure 18. The image has been reconstructed using the IR2 DN values and a fiducial system has been applied to the edges.

The section of Frame 1017-16093 containing Lake Koshkonong and a portion of the surrounding terrain is extracted from the tapes in each of the four MSS bands by supplying the computer with the appropriate coordinates. Figure 19 shows the extracted section for Band 7 (IR2). The histogram below the picture represented the full range of DN values present within the scene on a scale of 0 (black) to 255 (white). The prominent DN values, centered at approximately DN 128 and spreading symmetrically, are related to the land features within the section. The small cluster of DN values at the lower end of the DN scale is associated with water features including Lake Koshkonong and the Rock River.

In this study, the land DN values are of little interest and must be eliminated, leaving just the water body values. Previous testing has verified that the IR2 band is a good indicator of the areal extent of surface water. As was noted in Figure 19, IR2 water-related intensity values fall within the lower end of the DN scale and are essentially isolated from the land IR2 DN values. This characteristic permits the development of a binary mask which is used to eliminate the land image.

The mask is created by setting all intensity values at and below a specific numeric value equal to a value of one and setting all of the remaining DN values equal to zero. Each spatially equivalent Lake Koshkonong pixel within each band (green, red, IR1, and IR2) is multiplied by the IR2 binary mask. The net effect is to "zero out"

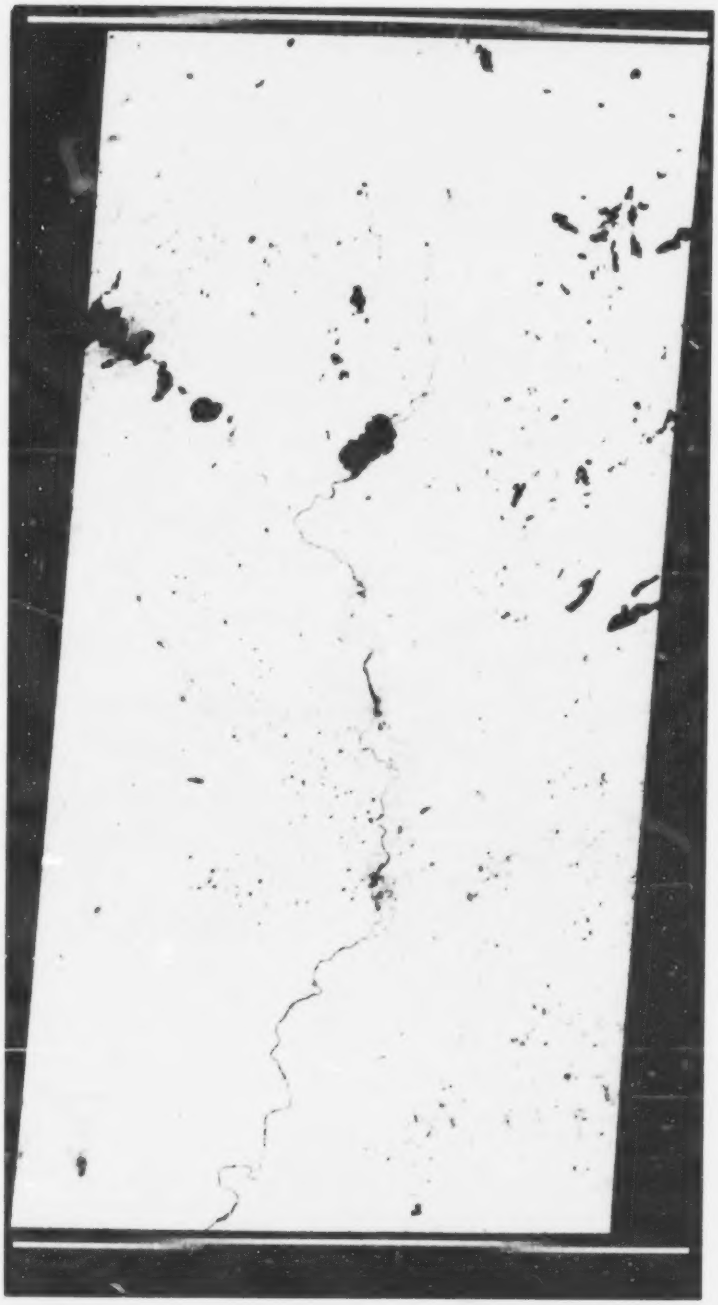


Figure 18. Left half of MSS Frame 1017-16093 reproduced using IR2 DN values. A fiducial system has been imposed along the edge of the image to aid in the determination of feature locations on the basis of line and picture element counts. Lake Koshkonong is the large dark object in the upper center of the photograph.

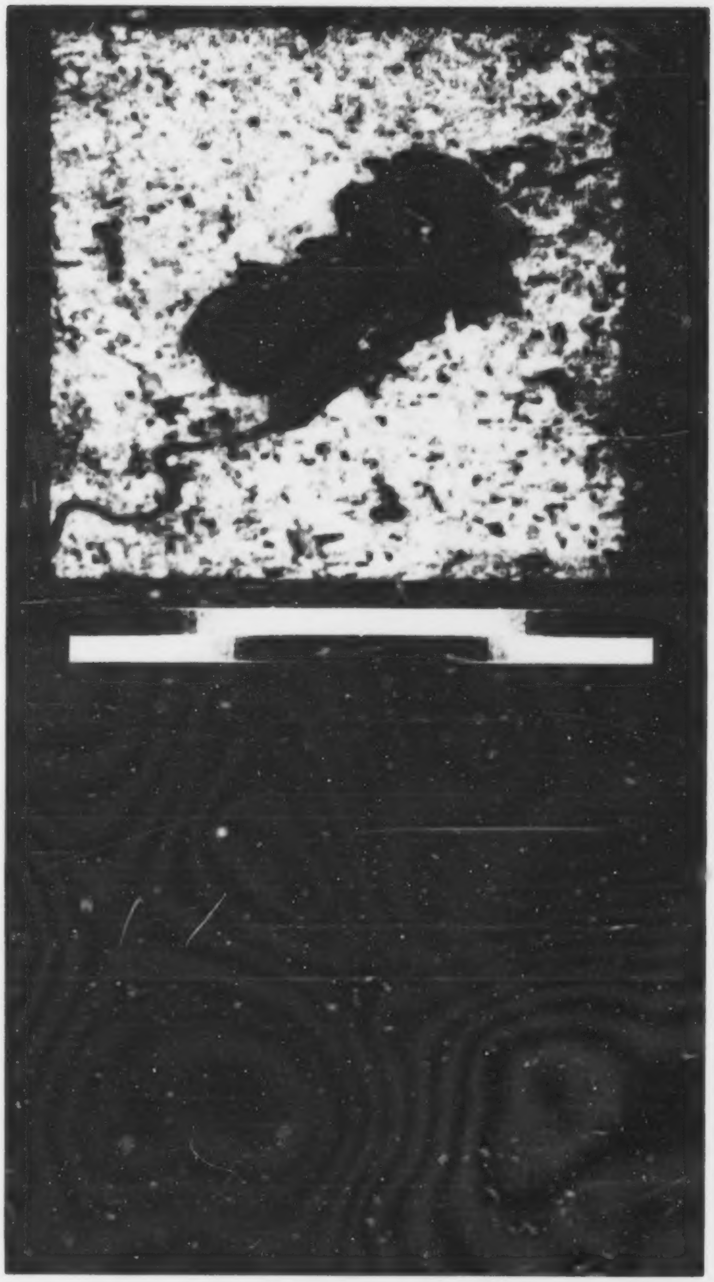


Figure 19. An extracted section of LANDSAT-1 MSS Frame 1017-16093. Lake Koshkonong, the Rock River, several small lakes and land features are evident. A histogram of the section, seen below the image, displays the range of DN values contained within the section. Water DN values cluster toward the lower end of the scale.

the unwanted background, leaving just the water features. Figures 20 and 21 were created by multiplication with a binary mask produced by setting all IR2 DN values of 28 or lower to a value of one. Images constructed from the IR1 and IR2 would be similar, showing only variations in the spectral signature for the water, and therefore in their pixel DN histograms.

A final cleanup is done by upgrading the binary mask prior to multiplying all of the bands. This is done by eliminating all of the smaller water bodies, streams, and swamp features which may be present. After the final cleanup and examination of a test multiplication, the mask is used on all of the bands for Lake Koshkonong. The pictorial expression of the final cleanup for the four spectral bands is depicted in Figure 22.

The concatenation technique is a very convenient method for summarizing the areal aspects of data extracted from the CCT's. Unlike line-printer copy, areal coverage afforded for several different lakes can be depicted in one simple photograph (e.g., Figure 23). Differences among the lakes in Figure 23 are not apparent because the range of IRs DN values is very small, and no effort has been made to enhance the images.

The VICAR photographic products displayed up to this point serve mainly to aid the investigator in the extraction of digital data from the CCT's. Typical numeric output from the system includes pixel counts, DN means and standard deviations for each of the four MSS bands, and histograms of the DN distributions. Pertinent data extracted from the example, Lake Koshkonong, are listed in Table 11.

TABLE 11. DESCRIPTIVE STATISTICS OF LAKE KOSHKONONG MSS DATA EXTRACTED FROM FRAME 1017-16093 CCT'S

	LANDSAT-1 MSS BANDS			
	Green	Red	IR1	IR2
DN Mean	46.85	31.15	27.95	10.08
DN Standard Deviation	1.814	2.446	2.933	2.890
Pixel Count	9,247	9,247	9,247	9,247

The DN values are used in determining correlations with ground (i.e., water) truth, developing regression models for selected lake trophic indicators and trophic state, and for image enhancement.

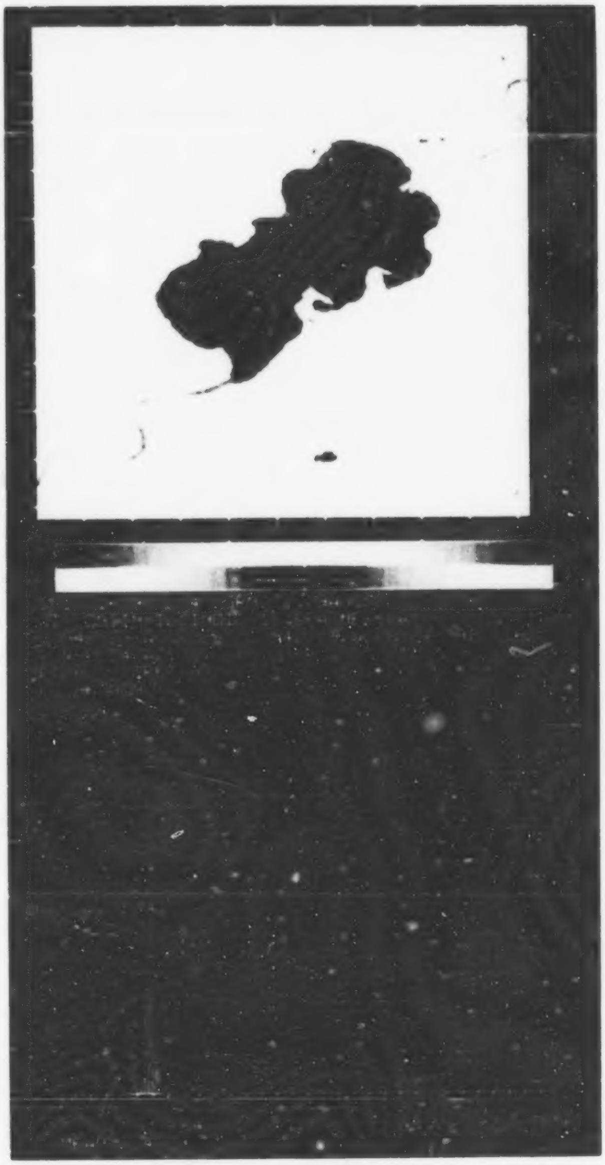


Figure 20. First-stage MSS Band 4 (GRN) cleanup picture of Lake Koshkonong. This picture was created by multiplying the Band Four scene equivalent of Figure 19 by the binary mask. All pixels corresponding spatially to IR2 pixels with DN values greater than 28 have been multiplied by zero, and thereby removed from the scene. The Rock River and miscellaneous water bodies still have to be eliminated.

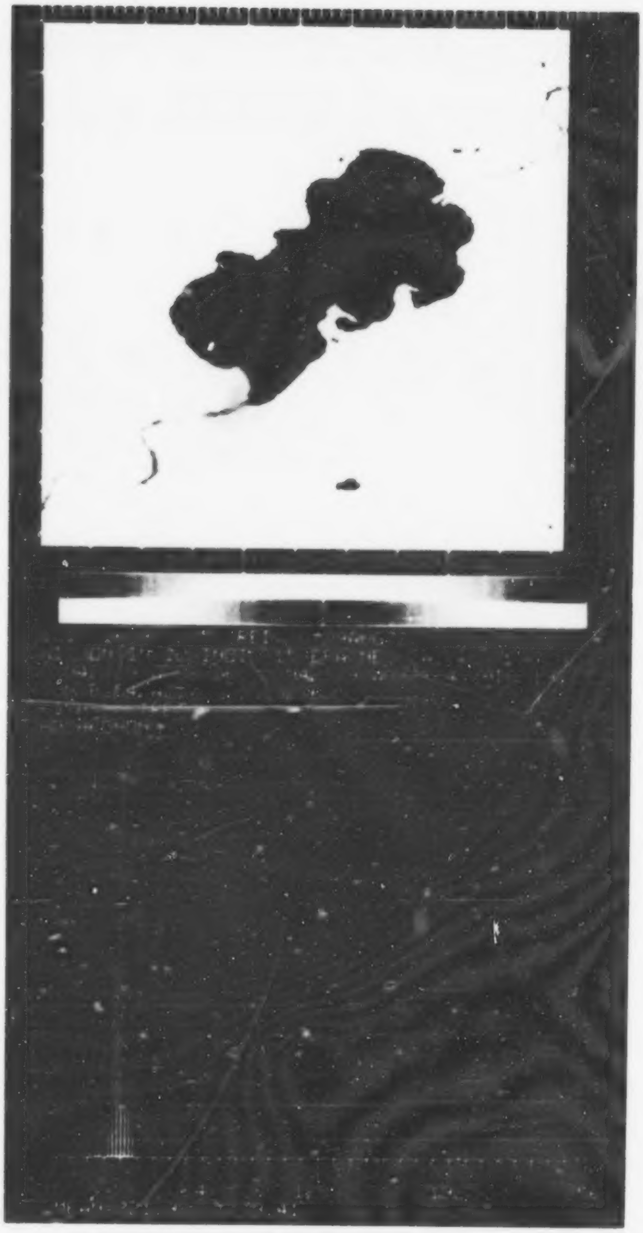


Figure 21. First-stage MSS Band 5 (RED) cleanup picture of Lake Koshkonong. This picture was created by multiplying the Band Five scene equivalent of Figure 19 by the binary mask. All pixels corresponding spatially to IR2 pixels with DN values greater than 28 have been multiplied by zero, and thereby removed from the scene.

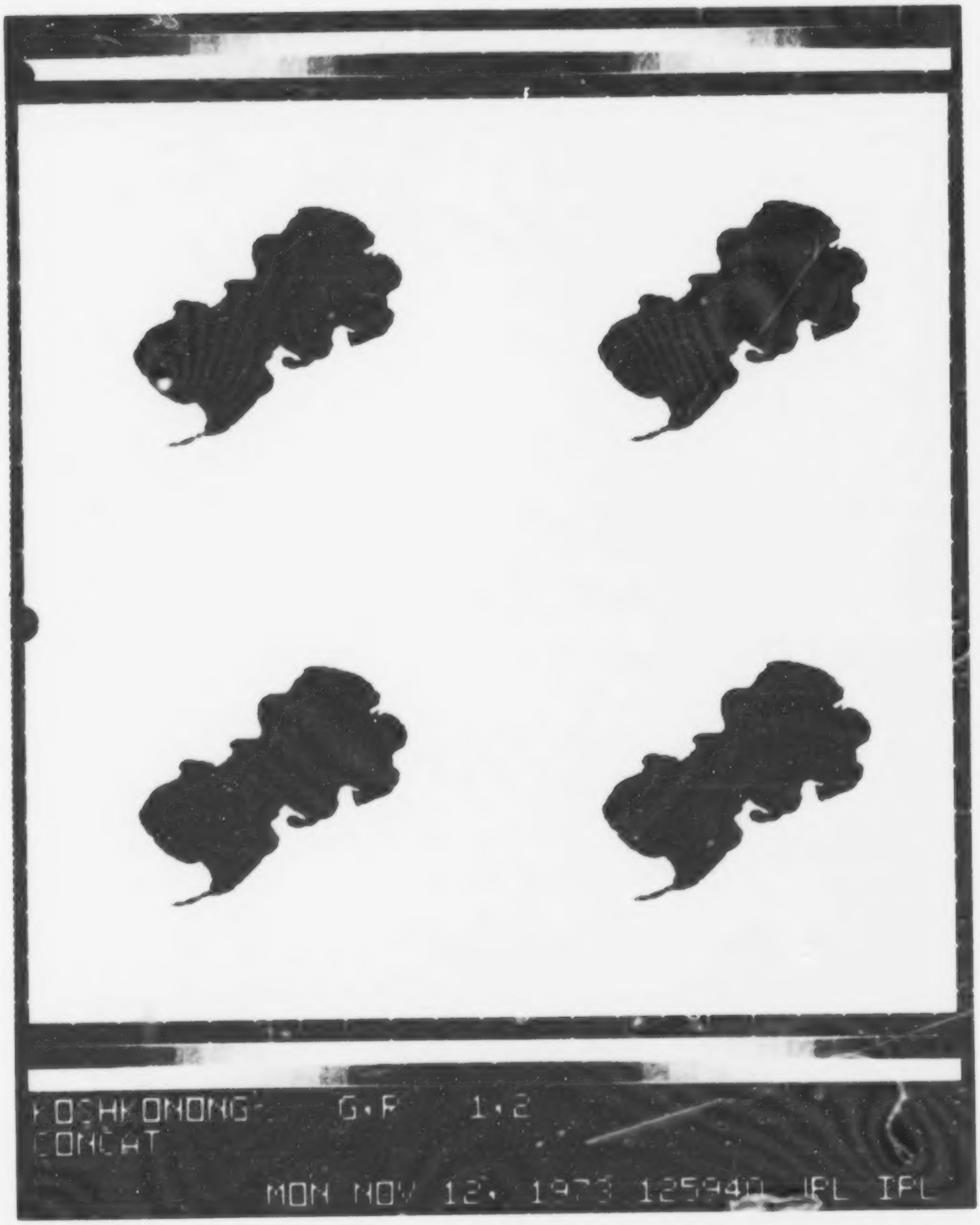
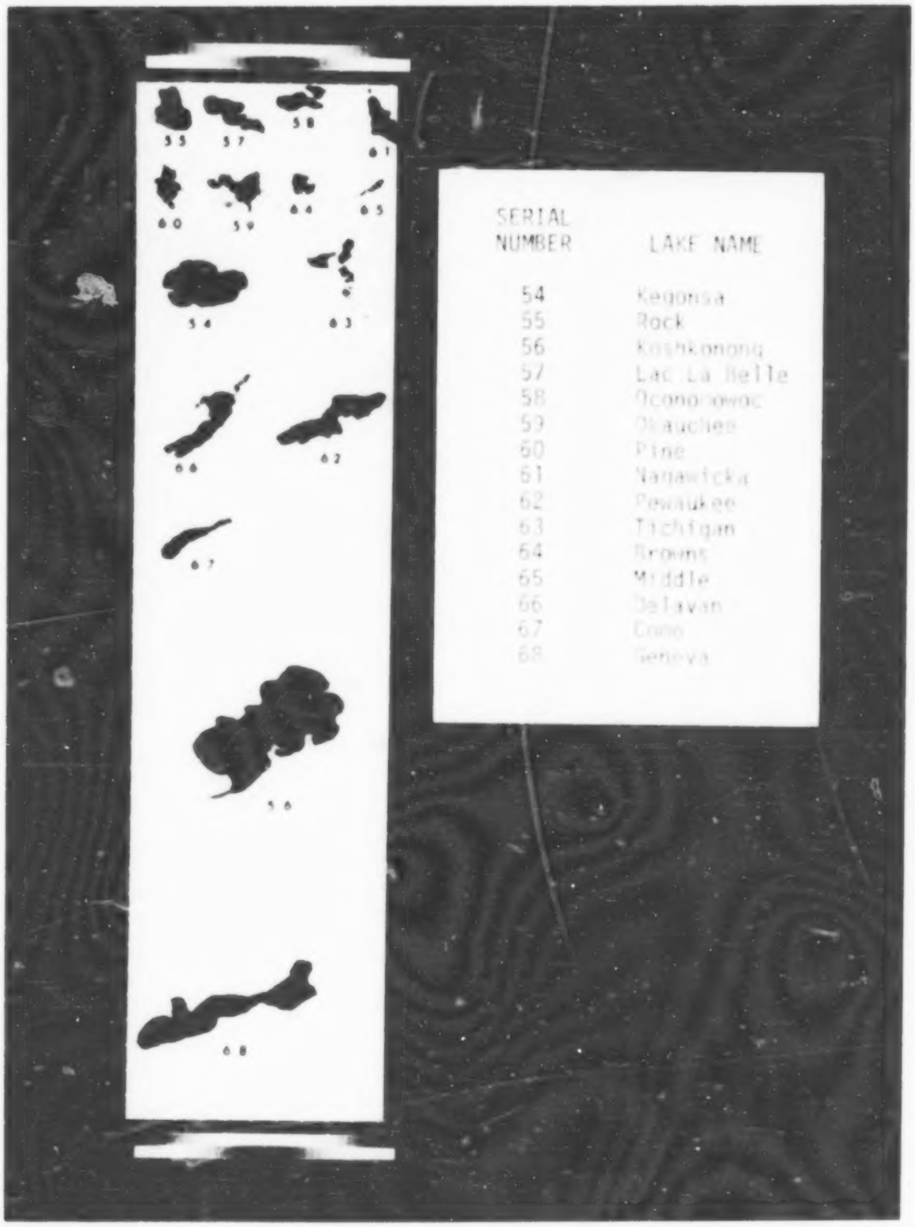

KOSHKONONG G.R 1.2
CONCAT
MON NOV 12, 1979 125940 JPL IPL

Figure 22. Four band (GRN, RED, IR1, IR2) concatenation of Lake Koshkonong after final cleanup. All of the unwanted land and water body pixels have been eliminated.



SERIAL NUMBER	LAKE NAME
54	Kegonsa
55	Rock
56	Koshkonong
57	Lac La Belle
58	Oconomowoc
59	Okauchee
60	Pine
61	Nagawicka
62	Pewaukee
63	Tichigan
64	Browns
65	Middle
66	Delavan
67	Como
68	Geneva

Figure 23. IR2 concatenation of 15 lakes extracted from LANDSAT-1 MSS Frame 1017-16093. The lake images are all reproduced at the same scale. However, they have not been skewed to correct the geometric distortion induced by the earth's rotation.

DIGITAL IMAGE ENHANCEMENT TECHNIQUES

Up to this point, the VICAR photographic output has served as an aid in the extraction of lake MSS DN values. However, the system can also enhance the digital images to bring out latent features. Two methods commonly employed are linear contrast stretching and a technique which utilizes color ratios. The techniques are briefly explained in this section along with several examples of the photographic output.

Color Ratio Technique

The color ratio technique consists of dividing the MSS DN values of one LANDSAT-1 band by another LANDSAT-1 band, pixel by pixel (i.e., data point by data point). Water colors which are difficult to discriminate generally have spectral reflectivity curves with similar but not identical slopes (Blackwell and Boland, 1974). The difference in the curve slopes will form the basis of the discrimination rather than absolute reflectivities. Application of the digital color ratio technique between selected bands will normalize the data by removing the common brightness components and will tend to emphasize differences due to slope.

The digital image of Lake Koshkonong (Frame 1017-16093) was enhanced using the ratio technique and subsequently reproduced in the form of a concatentation (Figure 24). Compare the enhanced images with Figure 22. It is readily apparent that considerable differences in lake color exist, particularly in the GRNRED, GRNIR1, and REDIR1 images. These ratios appear to merit further consideration. Additional information concerning ratio techniques and their applications is found in Billingsley and Goetz (1973).

Linear Contrast Stretching Technique

Another technique for detecting MSS color differences involves the enhancement of digital contrast of selected MSS bands through a "stretching" process. As is evident in Figure 18-23, the images of Lake Koshkonong are of very low contrast and essentially featureless. This is a consequence of the restricted DN value-range present for the lake in all MSS bands. An expansion of the lake's DN ranges to fill the entire black to white range (0 to 255) by linear expansion will enhance the contrast and bring out latent features. Stretching in the digital domain has the advantage that it does not suffer from the toe and shoulder saturations encountered with photographic stretching (Billingsley and Goetz, 1973).

The contrast stretch was performed on Lake Koshkonong data extracted from two LANDSAT-1 MSS frames (1017-16093, 9 August 1972; 1036-16152, 28 August 1972). The results are presented as Figures 25 and 26. The very strong banding effect is an artifact created by an inherent defect in the MSS system. A comparison of the lake images suggests that the MSS is capable of monitoring spatial-temporal changes in lakes. A scarcity of ground truth precludes a full interpretation of the physical significance of the patterns. This is one area in need of additional investigation.

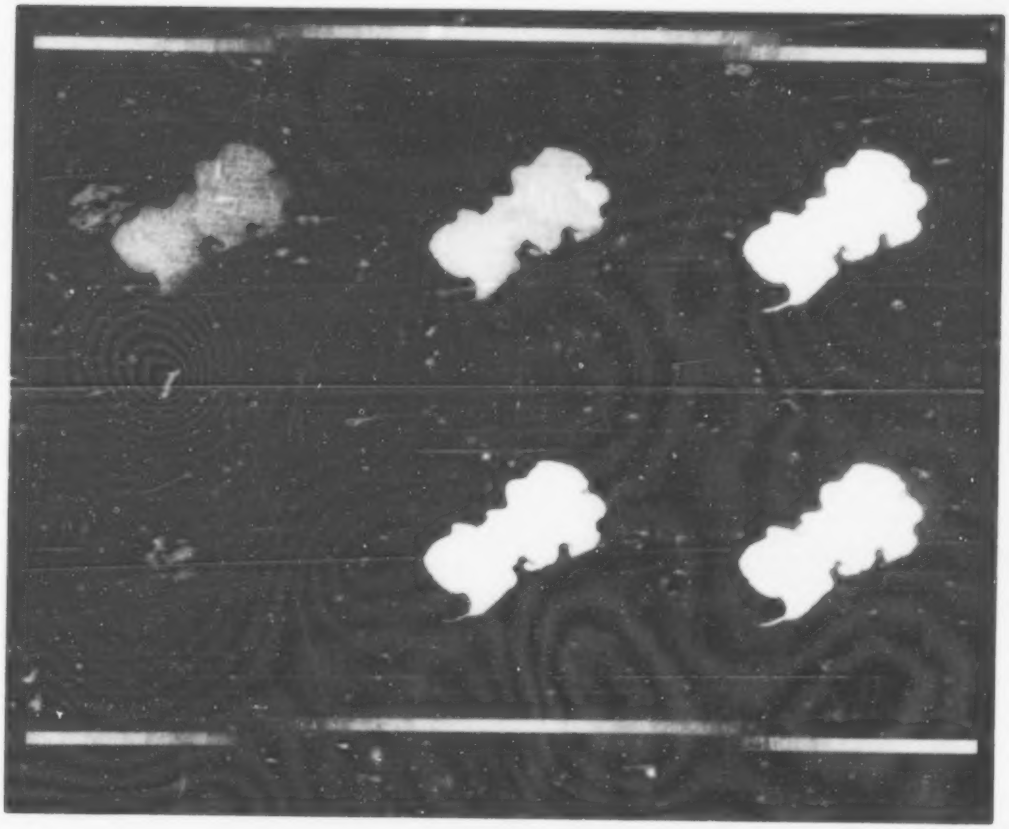


Figure 24. Lake Koshkonong image enhancement using six LANDSAT-1 MSS ratios. The ratios are, scanning from the top row left, GRNRED, GRNIR1, GRNIR2, REDIR1, REDIR2, IR1IR2. Differences in lake color are particularly evident among the GRNRED, GRNIR1, and REDIR1 ratios. The MSS data were extracted from Frames 1017-16093 (9 August 1972). Compare with Figure 22.

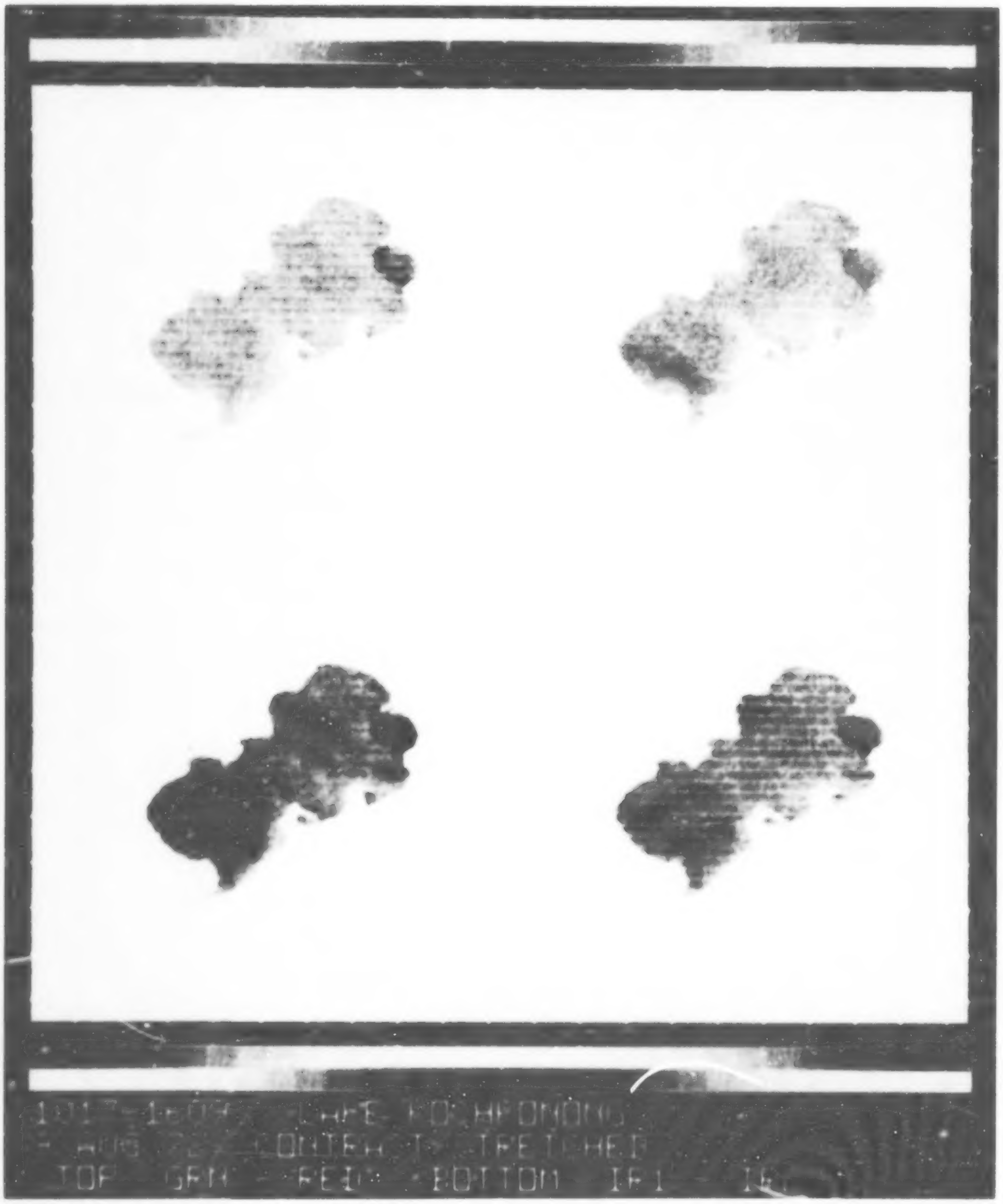

1017-16093 LAKE KOSHKONONG
9 AUG 72 CONTRAST STRETCHED
TOP GRN - RED BOTTOM IR1 - IR

Figure 25. Contrast stretched images of Lake Koshkonong. Frame 1017-16093 recorded by the LANDSAT-1 MSS on 9 August 1972. Upper row, left to right: GRN, RED; lower row, left to right: IR1, IR2. The banding or striping is an artifact.

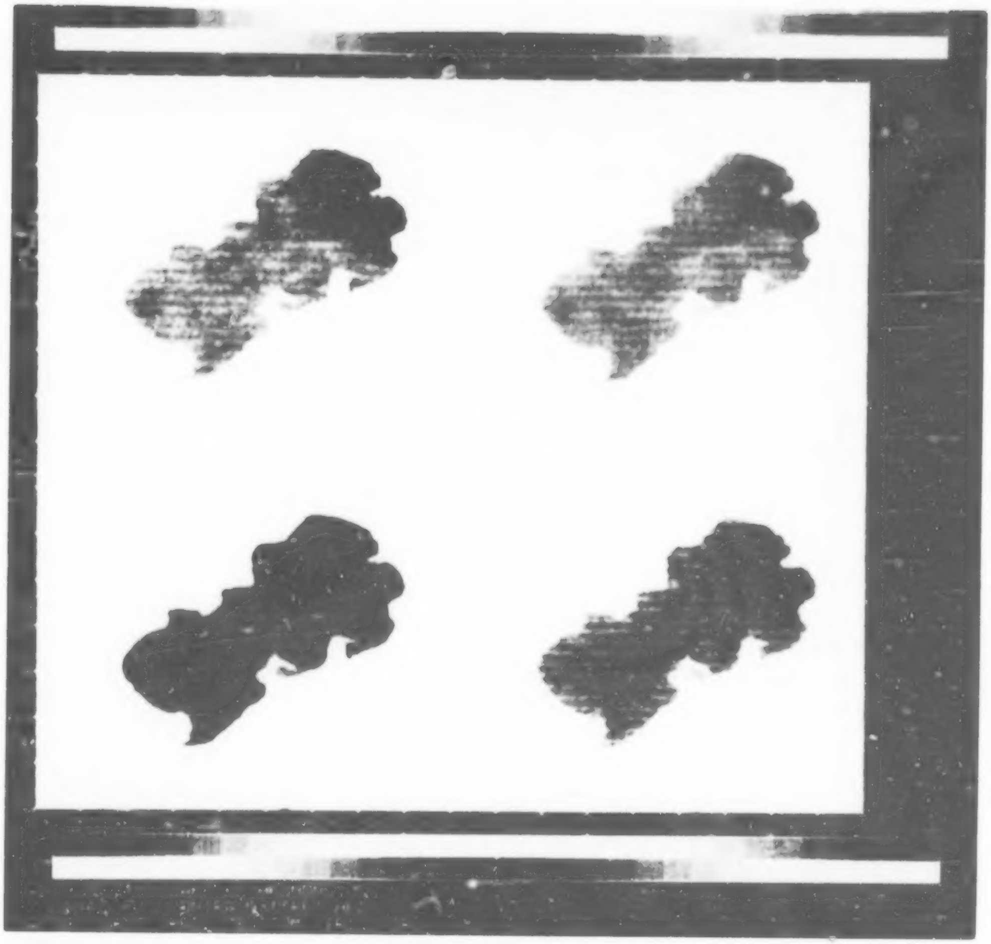


Figure 26. Contrast stretched images of Lake Koshkonong. Frame 1036-16152 recorded by the LANDSAT-1 MSS on 28 August 1972. Upper row, left to right: GRN, RED; lower row, left to right: IR1, IR2. Compare with Figure 25.

SECTION VI

LANDSAT-1 MSS-TROPHIC INDICATOR RELATIONSHIPS

This section is devoted to the evaluation of MSS data as a means of estimating the magnitude of trophic state indicators including Secchi disc transparency and chlorophyll a. In addition, lake surface area estimation is also examined.

OPTICAL PROPERTIES OF PURE WATER AND NATURAL WATERS

It is readily apparent, even to the casual observer, particularly if he or she is looking downward from an aircraft, that lakes differ in color and brightness. Many investigations have been undertaken to develop a comprehension of the processes which result in the observed phenomena. Although a detailed discussion of the interaction of electromagnetic energy with the components of the hydrosphere and atmosphere is outside the scope of this report, a brief survey is essential to gain some understanding of the principles which permit remote sensing and yet constrain its use in the assessment of trophic indicator magnitudes.

The interaction between electromagnetic energy and chemically pure water has been studied by numerous investigators (e.g., Ewan, 1894; Sawyer, 1931; Collins, 1925; James and Birge, 1938; Hulburt, 1945; Raman, 1922; Dawson and Hulburt, 1937). The transmission of electromagnetic energy through a material medium is always accompanied by the loss of some radiant energy by absorption. Some of the energy is transformed into other forms (e.g., heat, chemical) or to some longer wavelength of radiation (James and Birge, 1938). Pure water is very transparent to violet, blue and green light. In the infrared region, the extinction coefficient is high with a complementary low degree of transmission (Table 12). The absorption spectral characteristics of pure water can be modified greatly through the addition of dissolved and particulate materials.

The absorption spectra of natural waters (e.g., lake and ocean) have been studied in detail by Jerlov (1968), Duntley (1963), Atkins and Poole (1952), Birge and Juday (1929, 1930, 1931, 1932), and Juday and Birge (1933), to mention a few. Hutchinson (1957) has summarized the more important attempts to elucidate the interactions of light with natural waters, particularly in regards to lakes.

The attenuation of electromagnetic radiation in lake waters is a consequence of the relatively unselective effect of suspended particulate materials and the highly selective effect of dissolved coloring matter,

TABLE 12. OPTICAL PROPERTIES OF PURE WATER (ROOM TEMPERATURE)[a]

Wavelength (nanometers)	Extinction Coefficient	Percentile Absorption	Refractive Index
820 (infrared)	2.42	91.1	
800	2.24	89.4	
780	2.31	90.1	
760	2.45	91.4	1.329
740	2.16	88.5	
720	1.04	64.5	
700	0.598	45.0	
680 (red)	0.455	36.6	
660	0.370	31.0	1.331
640	0.310	26.6	
620 (orange)	0.273	23.5	
600	0.210	19.0	
580 (yellow)	0.078	7.0	1.333
560	0.040	3.9	
540	0.030	3.0	
520 (green)	0.016	1.6	
500	0.0075	0.77	
480	0.0050	0.52	1.338
460 (blue)	0.0054	0.52	
440	0.0078	0.70	
420	0.0088	0.92	
400 (violet)	0.0134	1.63	1.343
380 (ultraviolet)	0.0255	2.10	

[a] Adapted from Hutchinson (1957).

usually of organic origin, on the electromagnetic spectrum. The dissolved matter absorbs strongly in the violet and blue wavelengths, moderately in the middle wavelengths (e.g., green), and much less strongly at longer wavelengths (Hutchinson, 1957). When the dissolved materials are present in small quantities, the water will be most transmissive in the green wavelengths. Lake waters with large amounts of dissolved substances will be more transmissive in the orange and red wavelengths than in the shorter wavelengths. However, the transmission of the red and orange light is still greater in pure water than in water containing particulate and/or dissolved materials. As water transparency diminishes, the detectable electromagnetic energy will be of progressively longer wavelength, at increasingly shallower depths (Hutchinson, 1957).

Scherz, et al. (1969) have investigated the total reflectance (surface reflectance plus volume reflectance) curves of pure water and natural waters under laboratory conditions using a spectrophotometer. The resulting curve for distilled water is shown in Figure 27. They reported that the addition of dissolved oxygen, nitrogen gases, and salts (e.g., NaCl, Na_2SO_4, $Na_3PO_4 \cdot H_2O$) had no apparent effect on the reflection curve. However, water from lakes in the Madison (Wisconsin) area had reflectance curves that both differ from the distilled water curve and from each other. Scherz, et al. suggest that the differences can be attributed to the presence of different algal organisms. Filtration of the lake waters produced similar reflectance curves, though different from that of pure water (Figure 28).

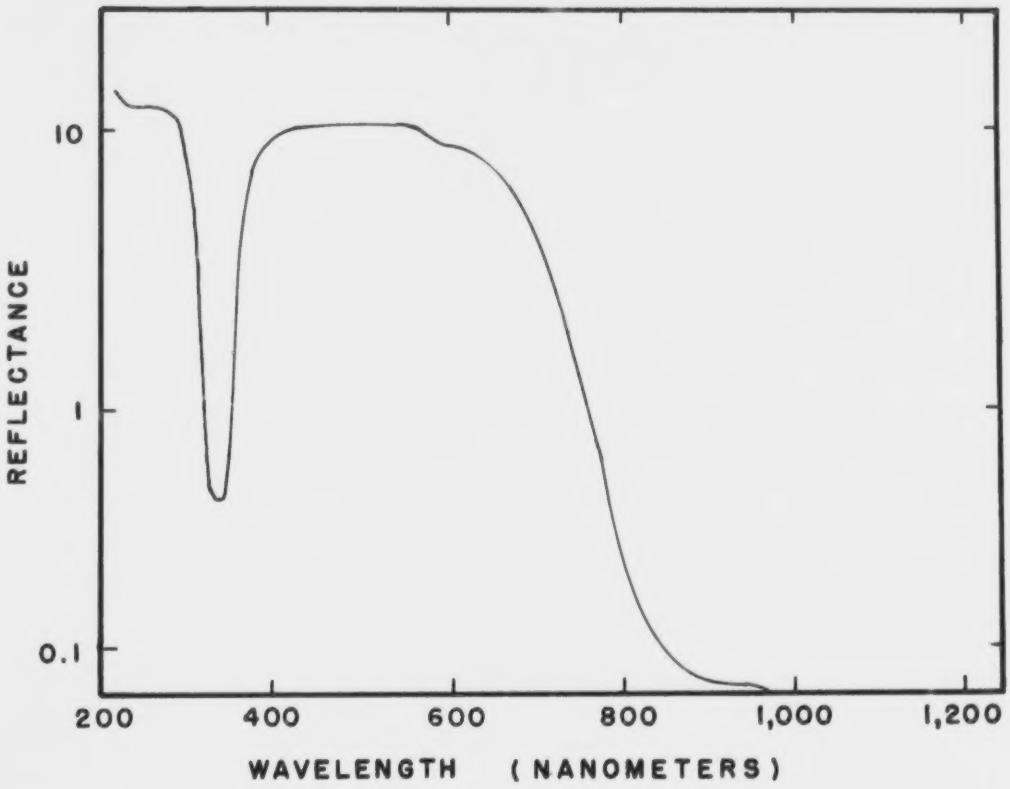
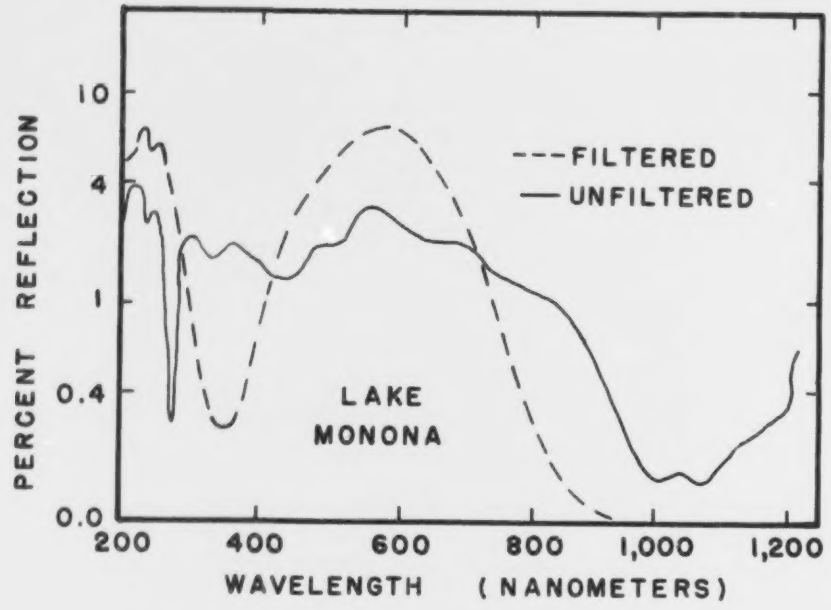


Figure 27. Reflectance curve for distilled water. Adapted from Scherz, et al. (1969).



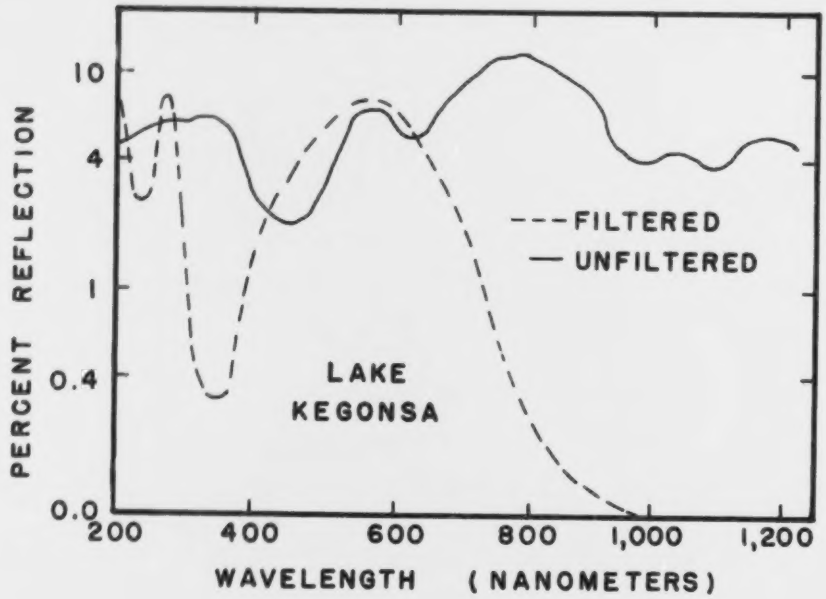


Figure 28. Reflection characteristics of filtered and unfiltered water samples from two Wisconsin lakes in the area of Madison. Adapted from Scherz, et al. (1969).

The color of a lake is the color of the electromagnetic energy backscattered from the lake body to the sensor. Lake color ranges from the blue of pure water through greenish blue, bluish green, pure green, yellowish green, greenish yellow, yellow, yellow brown, and clear brown (Hutchinson, 1957). It is a common practice to record lake color on an empirical scale such as the so-called Forel-Ule color scale, originally devised by Forel (1889) and subsequently modified and extended by Ule (1892). Lake color need not be, and is usually not the same as, the color of the lake water*.

Lakes which are blue in color lack appreciable quantities of humic materials and colored materials in suspension (e.g., phytoplankton). The bluer the lake color, the smaller the amount for free-floating organisms contained in the water (Ruttner, 1963). Water with high plankton content possess a characteristic yellow-green to yellow color. The characteristic color may not be apparent due to masking by other materials (e.g., suspended sediments). Ruttner (1963) suggested that

> A lake with very transparent and dark blue, blue-green, or green water is always oligotrophic. On the other hand, eutrophic lakes always have a relatively low transparency and are yellow-green to yellow brown in color; but the determination of these optical properties alone will not establish the productivity type, for the turbidity can be of inorganic origin, and the color can come from humic substances.

Seston color, attributable to the reflection spectra of suspenoids of microscopic or submicroscopic size, is often observed in highly productive lakes. Lakes containing large quantities of suspended inorganic matter (e.g., silt) may acquire a characteristic seston color, but in most cases the color is related to large concentrations of phytoplanktonic organisms (Hutchinson, 1957).

Peripheral Effects

The character of the electromagnetic energy impinging on the remote sensor, the LANDSAT-1 MSS in this case, has been shaped through interaction with numerous environmental phenomena.

The earth's atmosphere has a pronounced effect on the solar spectrum. The spectral distribution of the sun's radiation at the outer edge of the atmosphere and the normal energy distribution at the earth's surface are illustrated in Figure 29. Atmospheric conditions (e.g., degree of cloudiness; presence of fog, smoke, and dust; amount of water vapor) affect the degree of insolation attenuation. Weather conditions strongly affect the distribution of energy between sunlight and skylight (Piech and Walker, 1971), contributing a degree of uncertainty in water quality assessment through remotely sensed color measurements. Hulstrom (1973) has pointed out the adverse impact that cloud bright spots can have on remote sensing techniques which utilize reflected energy.

---

* Welch (1952) defines water color as "...those hues which are inherent within the water itself, resulting from colloidal substances or substances in solution" (i.e., true color). The platinum-cobalt scale (Hazen, 1892) has found favor in the United States for the determination of water color.

The degree of scattering and absorption imposed on the return signal from water bodies is related to the atmospheric transmittance and can result in changes in lake color when sensed at aircraft high flight and satellite altitudes. The attenuated return signal is also contaminated by electromagnetic radiation from the air column (path radiance). Rogers and Peacock (1973) have reported that solar and atmospheric parameters have a serious adverse impact on the radiometric fidelity of LANDSAT-1 data. Path radiance was found to account for 50 percent or more of the signal received by the MSS when viewing water and some land masses.

The magnitude of the adverse atmospheric effects can be reduced, though not completely eliminated, by using imagery or digital data collected on clear, cloudless days. This is the approach used in this investigation.

The LANDSAT-1 spacecraft passes over the same point on the earth at essentially the same local time every 18 days. However, even though the time of passover will remain essentially the same throughout the year, solar elevation angle changes (Figure 30) cause variations in the lighting conditions under which the MSS data are obtained. The changes are due primarily to the north or south seasonal motion of the sun (NASA, 1972). Changes in solar elevation angle produce changes in the average scene irradiance as seen by the sensor from space. The change in irradiance is influenced both by the change in the intrinsic reflectance of the ground scene and by the change in atmospheric backscatter (path radiance). The actual effect of changing solar elevation angle on a given scene is very dependent on the scene itself (NASA, 1972). For example, the intrinsic reflectance of sand is significantly more sensitive to changing solar elevation angle than are most types of vegetation (NASA, 1972). The effects of changing solar elevation angle are of particular importance when comparing scenes taken under significantly different angles. The use of color ratios in lieu of raw data values may be of value in reducing the magnitude of the solar angle induced effects by normalizing the brightness components. This is the approach used in this investigation.

A portion of the radiation impinging on the lake surface will be reflected. The percentage of surface-reflected energy is a strong function of the angle of incidence (Figure 31). Surface roughness is

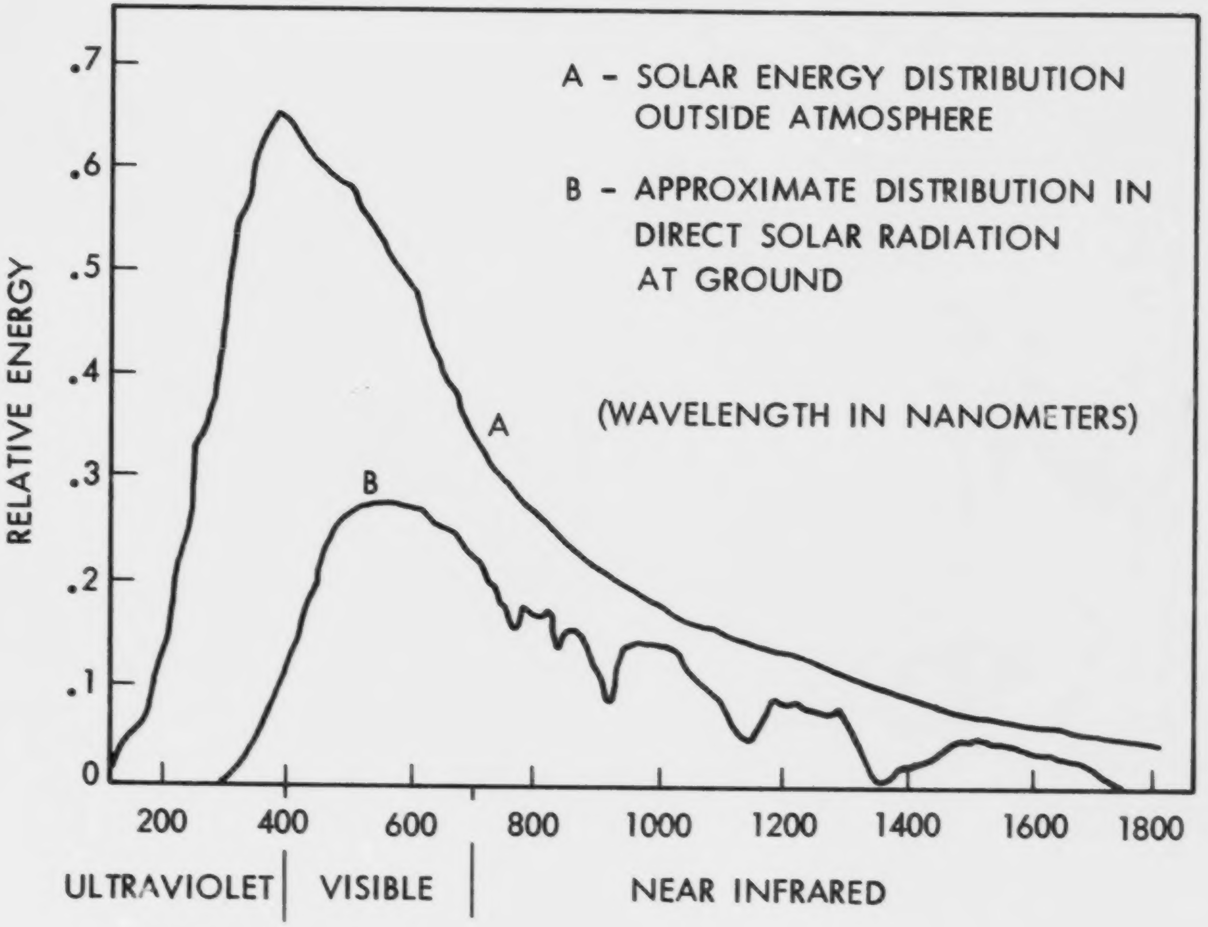


Figure 29. Spectral distribution of solar energy. Adapted from Hutchinson (1957).

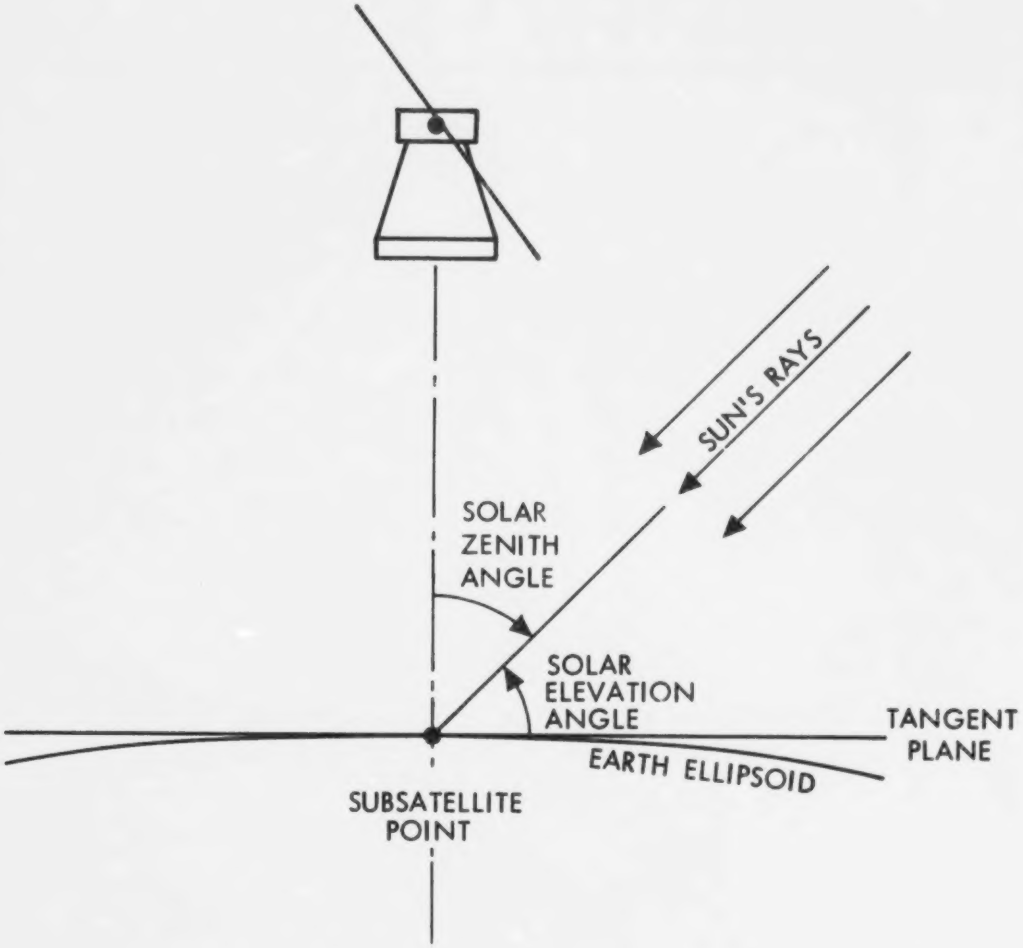

SUN'S RAYS
SOLAR ZENITH ANGLE
SOLAR ELEVATION ANGLE
TANGENT PLANE
EARTH ELLIPSOID
SUBSATELLITE POINT

Figure 30. Solar zenith and solar elevation relationship. Source NASA (1972).

known to have an effect on the percentages of light reflected and refracted at the interface (Jerlov, 1968). However, the effect of surface is negligible in estimating total radiation entering a water body when the solar elevation angle is greater than 15 degrees (Hutchinson, 1957).

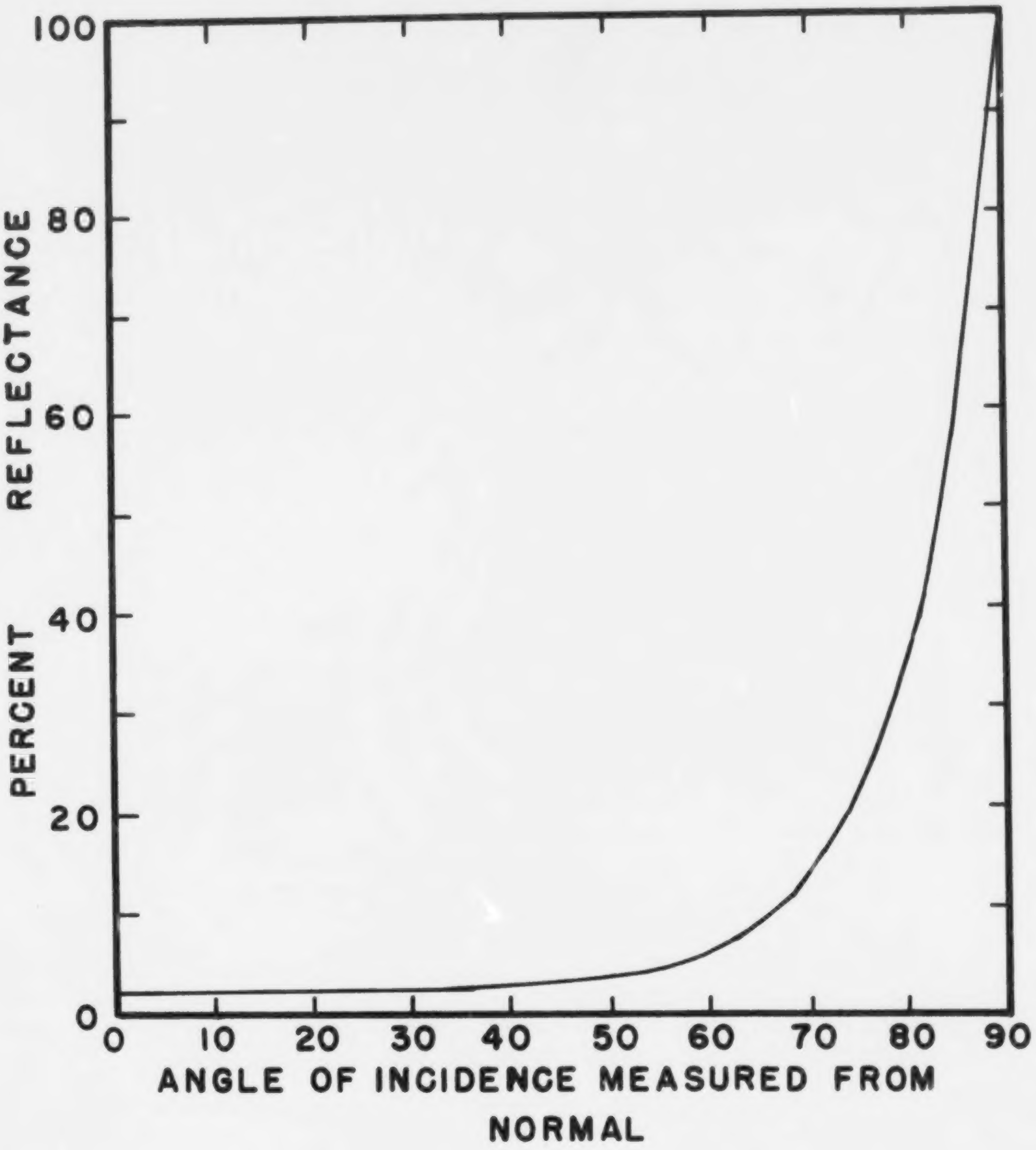


Figure 31. Percentage reflectance of the air-water interface as a function of the angle of incidence measured from normal direction. Values are for unpolarized light only. Source, Piech and Walker (1971).

The light reflected from the interface is composed of diffuse light from the sky (skylight) and specularly reflected sunlight. Specular reflection areas contained in a scene are of little value in most water studies, the possible exception being the determination of surface roughness. The specularly reflected radiation exceeds, by several orders of magnitude, the reflected energy emanating from beneath the water surface (Curran, 1972). Surface reflected skylight, containing no water quality color information, can compose from 10 percent of the return signal on a clear day to 50 percent on a cloudy day (Piech and Walker, 1971). The surface reflected skylight not only increases the apparent reflectance from the water body (volume reflectance), but also affects the shape of the reflectance curve.

An electromagnetic wave impinging on the surface of a lake decomposes into two waves, one of which is refracted, proceeding into the aquatic medium and a second wave which is reflected back to the atmosphere (Jerlov, 1968). The wave entering the water is refracted as it passes through the air-water interface according to Snell's Law which may be expressed as:

$$n = \sin i / \sin r$$

where (i) is the angle of incidence, (r) is the angle of refraction, and (n) is the refractive index, which for water is approximately 1.33 (see Table 12).

Most of the electromagnetic energy entering a lake is attenuated through the process of absorption. Although only a small percentage (less than 3 percent; Davis, 1941) of the incident energy is backscattered from the lake water volume, this light (volume reflectance) is the focus of interest in remote sensing of water quality investigations. Its spectral characteristics have been shaped by the materials found in the lake waters (dissolved and suspended materials, plankton, aquatic macrophytes, and air bubbles).

The lake bottom characteristics (color and composition) will also affect the intensity and/or the spectrum of the volume reflectance in settings where water transparency permits the reflection of a significant amount of radiation from the bottom materials. In studies involving the estimation of water depth or the mapping of bottom features, it is essential that the lake bottom be "seen" by the sensor. Bottom effects are capitalized upon and put to a beneficial use.

However, in this investigation, bottom effects are considered to be an undesirable peripheral effect. A sensor with the capabilities of the LANDSAT-1 MSS is not able to "see" much deeper into a lake than Secchi disc depth. The Secchi disc transparency of the selected NES lakes is, in most cases, relatively small when compared to the mean depth of each lake The assumption is made, as a first approximation, that bottom effect is relatively insignificant when considering each of the selected lakes as an entity.

It is evident that many factors influence the intensity and spectral characteristics of the electromagnetic radiation which is collected by the sensor. A peripheral effect, desirable in one study, may have a deleterious effect in another study. Absolute quantification of remotely sensed phenomena requires that all of the effects be accounted for in the return signal. Although the approach used here to reduce the magnitude of the undesirable peripheral effects might be criticized as simplistic or naive, it does serve as a starting point in the investigation of lake color-trophic indicator relationships using satellite-borne sensors. Although the results may be of a semi-quantitative nature, general trends in the data may be of value in lake classification studies.

RELEVANT REMOTE SENSING LITERATURE

A wealth of literature exists relating to the theoretical, applications, and instrumentation aspects of remotely sensed water quality. The advantages and limitations of remotely assessing water quality have been discussed by many investigators (Robinove, 1965; Hom, 1968; Kolipinski and Higer, 1968; Clarke, 1969; Fortunatov, 1957; Kiefer and Scherz, 1970, 1971; Conrod and Rottweiler, 1971; Gramms and Boyle, 1971; Scherz, 1971; Clapp, 1972; Wezernak and Polcyn, 1972; Colwell, 1973).

Wezernak and Polcyn (1972) examine the question of making eutrophication assessments from the standpoint of current remote sensing technology. They suggest, that of some 16 factors which often serve as measures of eutrophication (Table 13), several can be remotely sensed using operational and near-operational systems. The parameters include chlorophyll, colored water masses, suspended solids, transparency, aquatic macrophytes, and algal blooms. In addition, remote sensing technology can also provide an economic method of obtaining morphometric and land use information (e.g., shoreline development, lake surface area, and cultural impact) which has a direct bearing on the trophic state of a water body.

Most of the water-oriented investigations have focused on the oceanic environment and point source pollution of fresh waters using aerial photography (black and white, color, black and white infrared, color infrared, multispectral). Investigations utilizing airborne multispectral scanners and lasers are becoming increasingly common. Many aspects of water quality have been examined using remote sensors mounted on non-satellite platforms; pertinent aspects are discussed below.

Remotely determined estimates of chlorophyll levels in natural waters (*in situ*) have been made by several investigators (Clarke, *et al*., 1969,

TABLE 13. INDICES COMMONLY USED TO ASSESS EUTROPHICATION[a]

Standing crop of algae and aquatic plants[b]
Amount of suspended solids[b]
Volume of algae
Chlorophyll levels[b]
Number of algal blooms[b]
Transparency[b]
Plant regression[b]
Photosynthesis
Primary production
Aquatic plant nutrient content
Hypolimnetic oxygen concentrations
Sediment composition
Dissolved solids
Conductivity
Nutrient concentrations
Cation ratio (Na + K) / (Mg + Ca)

---

[a] Adapted from Wezernak and Polcyn (1972).
[b] Index can be remotely sensed using operational or near-operational sensors.

1970; Mueller, 1972; Curran, 1972; White, 1969; Atwell and Thomann, 1972; Arvensen, et al., 1971; Bressette and Lear, 1973). Curran (1972) reported a strong correlation between wavelength-dependent albedo ratios, made from measurements collected by high-flight aircraft, and phytoplankton chlorophyll concentrations, from satellite altitudes, to an uncertainty of 0.1 mg/m^3. Blackwell and Billingsley (1973) have utilized multispectral photography in conjunction with digital computer enhancement techniques to detect algae. Crew (1973) has mapped and identified an algal species in Clear Lake (California) employing an airborne multispectral scanner.

Aerial photography, utilizing color and color-infrared films, is a relatively simple technique that has demonstrated utility in mapping aquatic macrophytes (Kolipinski and Higer, 1968; Kiefer and Scherz, 1971) and shallow water benthos (Kelly and Conrod, 1969). Photographs are used routinely to map wetlands (Anderson and Wobber, 1973). It is an accepted practice to use aerial photographs in the delineation and enumeration of lakes (Minnesota Department of Conservation, 1968).

Remote sensors are employed to estimate water turbidity (Crew, 1973; Schmer, et al., 1972, Williams and Samol, 1968). Some investigators (Brown, et al., 1972; Specht, et al., 1973) have used remote sensors to estimate water depth and bottom topography. Dybdahl (1973) has demonstrated an airborne remote sensing technique for the determination of dissolved oxygen levels in fresh water.

Relevant LANDSAT-1 Investigations

Prior to the insertion of LANDSAT-1 into its near-polar orbit, investigators interested in assessing and monitoring the earth's natural resources from satellite altitudes were restricted to using poorly suited satellite-borne sensors. The spacecraft were largely equipped with sensors designed for studies oriented toward the atmosphere or, in some cases, the ocean.

The length of the list of NASA-designated LANDSAT-1 principal investigators -- some 300 are found on it (Data Users Handbook, Appendix M, February, 1972) -- suggests that there is a great interest in assessing the advantages and limitations of remotely sensing the earth's resources from satellite altitudes. The major focus, as evidenced by project titles, is on the terrestrial environment; less than 10 percent of the investigations relate to water quality and the majority of these concentrate on the oceanic environment and the Laurentian Great Lakes. Some of the water-related investigations bear mentioning.

Wezernak and Polcyn (1972) have detected a municipal-industrial waste disposal in the New York Bight. Lind and Henson (1973) and Lind (1973) have discovered and documented a pollution plume emanating from a mill located on the shore of Lake Champlain. It is apparent from a literature review that the detection of large turbidity plumes and turbidity related patterns is easily accomplished using the LANDSAT-1 multispectral scanner-generated imagery (*e.g.*, Watanabe, 1973; Klemas, 1973; Carlson, 1973; Wright, Sharma, and Burbank, 1973; Pluhowski, 1973; Coker, Higer, and Goodwin, 1973; Kritikos, Yorinks, and Smith, 1973).

Enhanced and density-contoured imagery appears to permit water depth estimation to a depth of at least five meters in the clear waters around the Bahama Islands (Ross, 1973). Polcyn and Lyzenga (1973), using digital processing techniques on an LANDSAT-1 MSS frame taken over the Bahama Islands, have mapped shallow water features and calculated water depths to five meters. The waters in the area are known for their clarity and are conducive to remote sensor mapping activities.

Hidalgo, *et al*. (1973) have identified large mats of duckweeds (*Lemnaceae*) on Lake Pontchartrain and surrounding bayous and swamps in southeastern Louisiana. Seasonal changes have been detected. Strong (1973) has noted algal blooms in Utah Lake (Utah) and in Lake Erie.

Barr (1973) has mapped a total of 2,272 water bodies in Saline County (Kansas) where a topographic map (1955) indicates 1,056. A preliminary comparison of imagery and maps indicates that bodies larger than four hectares (10 acres) are consistently detectable. Most water bodies between about two to four hectares are usually detectable; water areas less than two hectares are occasionally resolved. Erb (1973), using nine-inch-square transparencies, has determined that ponds as small as one hectare are detectable within forested areas. The initial findings of Chase, Reed, and Smith (1973) indicate that water bodies of about 0.5 hectares are detectable under fair conditions (haze and 70 percent cloud cover); distortion of lake size, shape, and orientation is minimal. The benefits of using LANDSAT-1 imagery to enumerate lakes have been demonstrated by Reeves (1973) and Work, *et al*. (1973).

Yarger, *et al*. (1973), using electronically sliced imagery, have found a good correlation between suspended load (predominantly composed of inorganic materials) and film densities of two federal reservoirs in Kansas. Bowker, *et al*. (1973) reported that there appears to be a positive correlation between particulate count and chlorophyll level in Lower Chesapeake Bay. A rough correlation exists between suspended sediments and MSS imagery, but no correlation is apparent for the chlorophyll bearing portion of the load. Szekielda and Curran (1972) indicate that a correlation exists between chlorophyll and LANDSAT-1 MSS imagery (green band) in the general area of St. John's River estuary in Florida.

Rogers and Smith (1973), reporting on their investigation of six lakes in Michigan, suggested that deep water and shallow water can be separated by a trained photo-interpreter using reflectance printout gray-scales or a cathode tube monitor. Lakes were best discriminated in band seven (IR2) due to the strong contrast between land and water (Rogers and Smith, 1973). Classifying lake eutrophication on the basis of algal scum or macrophytes in shallow water appears to be a "straight-forward" matter with LANDSAT-1 MSS data. Estimations of water depth may be possible in some lake areas where there are extensive shallows and the water is clear and unencumbered with vegetation (early spring).

TROPHIC INDICATOR ESTIMATION

Although the LANDSAT-1 provides 18-day cyclic coverage, a point stressed in many of the reports and articles written on the spacecraft, obtaining good coverage in the study area was (and still is) a major problem. This is a problem shared with many other investigators. On numerous dates of coverage, cloud cover was excessive (greater than 10 percent) and on several occasions, when the weather conditions were conducive to monitoring the lakes, one or more of the MSS bands were either missing or rated as poor. The formation of ice cover on the study lakes, lasting for several months, further reduced the opportunity to obtain repetitive coverage.

A search of the LANDSAT-1 MSS imagery and CCT's for the study area (Minnesota, Wisconsin, Michigan, New York) for the period from August, 1972 through July, 1973, resulted in the selection of the frames found in Table 14. The lakes which were examined in this investigation are listed in Table 15. Several additional frames were not included because they contain less than three lakes sampled under the National Eutrophication Survey Program. Frames from the 1973 calendar year were not selected if LANDSAT-1 MSS coverage was not available for the 1972 sampling year.

TABLE 14. LANDSAT-1 MSS FRAMES

Frame Number	Date	Area	Number of Lakes
1017-16091	9 August 1972	Eastern Wisconsin	5[b]
1017-16093	9 August 1972	Southeastern Wisconsin	15[b]
1036-16152	28 August 1972	South central Wisconsin	6
1323-16094	11 June 1973	Eastern Wisconsin	4[b]
1323-16100	11 June 1973	Southeastern Wisconsin	23[b]
1359-16091	17 July 1973	Eastern Wisconsin	4[b]
1359-16094	17 July 1973	Southeastern Wisconsin	18[b]
1022-16373	14 August 1972	Central Minnesota	12
1075-16321	6 October 1972	Central Minnesota	15
1077-16431	8 October 1972	West central Minnesota	10
1309-16325	28 May 1973	Central Minnesota	13
1345-16322	3 July 1973	East central Minnesota	14
1346-16381	4 July 1973	Central Minnesota	8
1027-15233	19 August 1972	Northwestern New York	7
1080-15180	11 October 1972	Northwestern New York	5

[a] Lakes extracted from frames recorded on the same flightline and data are pooled to increase sample size.

[b] Some of the lakes appear in both frames; e.g., Lake Winnebago is often split between two frames.

TABLE 15. DATES OF LANDSAT-1 COVERAGE

Lake Name and Serial Number		LANDSAT-1 Coverage Data											
		1972							1973				
		9 Aug	14 Aug	19 Aug	28 Aug	6 Oct	8 Oct	11 Oct	28 May	11 June	3 July	4 July	17 July
Shawano	46									X			X
Butte des Morts	47	X								X			X
Poygan	48	X								X			X
Winnebago	49	X								X			X
Green	51	X								X			X
Beaver Dam	53	X								X			X
Kegonsa	54	X			X					X			X
Rock	55	X			X					X			X
Koshkonong	56	X			X					X			X
Lac la Belle	57	X								X			X
Oconomowoc	58	X								X			X
Okauchee	59	X								X			X
Pine	60	X								X			X
Nagawicka	61	X								X			X
Pewaukee	62	X								X			X
Tichigan	63	X								X			X
Browns	64	X								X			X
Middle	65	X								X			X
Delavan	66	X								X			X
Como	67	X								X			X
Geneva	68	X								X			X
Mendota[a]	108				X					X			
Monona[a]	109				X					X			
Waubesa[a]	110				X					X			
Darling	16		X				X						
Carlos	17						X						
Le Homme Dieu	18		X				X						
Minnewaska	19		X				X						
Nest	20		X				X					X	
Green	21		X				X					X	
Wagonga	22		X				X					X	
Clearwater	23		X			X			X		X		
Maple	24		X			X			X		X		
Cokato	25		X			X			X		X	X	
Buffalo	26		X			X			X		X	X	
Carrigan	27					X			X		X	X	

TABLE 15. DATES OF LANDSAT-1 COVERAGE (continued)

Lake Name and Serial Number		LANDSAT-1 Coverage Data											
		1972							1973				
		9 Aug	14 Aug	19 Aug	28 Aug	6 Oct	8 Oct	11 Oct	28 May	11 June	3 July	4 July	17 July
Silver	28		X			X			X		X	X	
Minnetonka	29		X			X					X		
Forest	30					X			X		X		
White Bear	31					X			X		X		
St. Croix	32					X			X		X		
Spring	33					X			X		X		
Pepin	34					X							
Madison	35					X			X		X		
Sakatah	36								X		X		
Winona	101						X						
Trace	102						X						
Calhoun	103					X			X		X		
Big Stone	104						X						
Zumbro	105					X							
Cottonwood	111											X	
Conesus	91			X									
Canandaigua	92			X									
Keuka	93			X									
Seneca	94			X									
Cayuga	95			X				X					
Owasco	96			X				X					
Cross	97			X				X					
Oneida	106							X					
Canadarago	107							X					

---

[a] This lake fell outside the scope of the National Eutrophication Survey Program, but was included here because it is a well-known lake on which considerable eutrophication research has been conducted.

Every effort was made to get MSS coverage which was concurrent with the collection of the ground truth by the helicopter-borne field teams. This goal was achieved in the case of only one frame (1080-151800). Unfortunately the number of NES sampled lakes contained in the frame is too small to incorporate into a regression model. The dates on which ground truth was collected from the study lakes are found in Appendix B.

Ideally, the estimation of the magnitude of trophic state indicators should be done using concurrent data to derive the maximum benefit. However, in this investigation it was necessary to use what may be called "near concurrent" ground truth which was collected several days before or after satellite overflight. Nevertheless, models developed from such a temporal arrangement are of some value in illustrating general relationships existing between the MSS data and ground truth.

Estimations of the magnitude of two trophic state indicators (chlorophyll a and Secchi disc transparency), using LANDSAT-1 MSS data and NES collected ground truth, are demonstrated in the remainder of this section using two of the frames in Table 14. The frames, 1017-16091 and 1017-16093, are treated as one frame to increase the lake sample size. The frames are in juxtaposition on the same flightline, were recorded on the same day, and prior to Goddard Space Flight Center Processing, were elements in a continuous strip. The frames were selected on the basis of temporal proximity to NES ground truth dates, the quality of the MSS data (good MSS band ratings, little cloud cover and haze), and the presence of a relatively large number of NES lakes (N=20). An examination of Table 15 indicates that coverage is available for the same 20 lakes on two other occasions.

MSS frames from 12 different dates and three states (Minnesota, Wisconsin, and New York) are examined in this report. The fragmentary LANDSAT-1 coverage, very evident in Table 15, makes it difficult to give a coherent demonstration of the MSS's capabilities and limitations. In an attempt to reduce the magnitude of the problem, the author has taken the liberty of focusing on the Wisconsin frames and relegating the other frames to Appendix D. The appendix is divided into a series of subappendices (one for each LANDSAT-1 date) which contain descriptive statistics of the MSS data, LANDSAT-1 MSS estimates of lake area, area ratios, lake concatenations, three-dimensional color ratio models, and regression models.

Data reduction was accomplished on the Oregon State University CDC 3300 computer using the Statistical Interactive Programming System (SIPS). The regression models were developed using the backward selection procedure (Guthrie, et al., 1973). The backward method was selected largely on the basis of its intuitive appeal.

LANDSAT-1 Lake Area Estimation

A straightforward method of estimating the area of an extracted lake involves a summation of the pixel counts in one band (*e.g.*, IR2) and subsequent multiplication by a conversion factor of 0.48 (1 pixel = 0.48 ha = 1.18 ac) to get the area in hectares. The conversion factor used here was obtained from R. J. Blackwell (personal communication, 1973). A comparison of lake area estimations from other sources with LANDSAT-1-derived area values acts as a check to verify that the pixels and their respective DN's are those of the water body under scrutiny. A topographic area/LANDSAT-1 area ratio greater than one indicates that the extracted image is smaller than the area covered by the MSS lake image. A ratio less than one suggests that the extracted image includes wet lands and/or land features. Underestimation of lake size is preferable to overestimation (inclusion of wetland and/or land) in this study. The surface areas of the 20 lakes extracted from Frames 1017-16091 and 1017-16093 are generally within 10% of values derived from U.S.G.S. topographic sheets and publications of the Wisconsin Department of Natural Resources (see Table 16).

Discrepancies between LANDSAT-1 and topographic sheet-derived area estimates may be a consequence of: changes in the lake area since the topographic sheet was constructed; inaccurate delineation of the shoreline on aerial photographs or during the preparation of the sheet; inclusion of wetlands or exclusion of portions of the lake during the preparation of the IR2 binary mask; or failure to use a correct conversion factor.

The estimated lake areas using LANDSAT-1 MSS pixel counts are in good agreement for most of the lakes in Table 16. The very large error for Middle Lake is due to the contiguous nature of the Lauderdale Lakes. The computer extraction process resulted in a sample taken from the area mapped as Middle Lake. Some of the lakes, particularly those which occupy shallow basins, are known to fluctuate greatly in surface area and topographic sheets do not account for the variation.

Adding the 20 lake areas derived from the topographic sources and then comparing the resultant value with the composite LANDSAT-1 MSS lake area value, excluding Middle Lake, results in a ratio of 1.016:1.000. A visual examination of the area ratios for the other frames (see the subappendices of Appendix D) indicates that the MSS can be used to give good estimates of lake surface area when a DN value of 28 is used as the "cutoff" point in extracting the lakes from their terrestrial matrix. The lake area estimation capabilities of the MSS are of value, not only in the study of lakes with established areas, but also in geographic regions for which there is no accurate topographic or aerial photographic coverage.

The photographic products (concatenations), fabricated by the VICAR system, are of immense value in extracting the lake "images" stored on

TABLE 16. AREAL ASPECTS OF 20 NES-SAMPLED LAKES EXTRACTED FROM LANDSAT-1 MSS FRAMES 1017-16091 and 1017-16093.

Lake Name	Serial Number	Pixel Count	LANDSAT-1 Lake Area (ha)	Map Lake Area (ha)	Map Area: LANDSAT-1 Area Ratio
Poygan	47	9,177	4,382.5	4,448.5	1.015
Butte des Morts	48	7,395	3,531.5	3,584.4	1.015
Winnebago	49	114,186	54,529.1	55,730.4	1.022
Green	51	6,613	3,158.0	2,972.9	0.942
Beaver Dam	53	5,162	2,465.1	2,671.0	1.084
Kegonsa	54	2,675	1,277.4	1,099.2	0.861
Rock	55	1,009	481.8	554.8	1.152
Koshkonong	56	9,247	4,415.9	4,241.3	0.961
Lac la Belle	57	944	450.8	452.1	1.003
Oconomowoc	58	652	311.4	317.7	1.015
Okauchee	59	871	415.9	450.8	1.085
Pine	60	568	271.3	284.5	1.049
Nagawicka	61	751	358.6	415.2	1.155
Pewaukee	62	1,996	953.2	1,008.9	1.058
Tichigan	63	689	329.0	449.8	1.367
Browns	64	309	147.6	160.3	1.086
Middle	65	117	55.9	104.8	1.876[a]
Delavan	66	1,541	735.9	717.9	0.976
Como	67	703	335.7	383.0	1.151
Geneva	68	4,543	2,169.5	2,129.5	0.982

[a] Middle Lake is contiguous with Mill Lake and Green Lake; the lakes are commonly referred to as the Lauderdale Lakes. The extraction process resulted in a sample of the area mapped as Middle Lake. The Green Lake of the Lauderdale Lakes is not to be confused with Green Lake (51).

the CCT's. They permit the investigator to examine the extracted lake for geometric fidelity, truncation of the water body, and for the inclusion of other water bodies. The photographic products are superior to output in the form of line printer copy in studies relating to the areal aspects of water bodies.

Secchi Disc Transparency Estimation

Although it is beyond the capabilities of the MSS to directly measure chemical indicators, its areal and spectral resolution permit the detection of phenomena related to eutrophication (such as Secchi disc transparency, chlorophyll a) together with some degree of quantification.

An R-mode Pearson product-moment correlation analysis was made using the MSS data and ground truth collected from the 20 NES lakes in Frames 1017-16091 and 1017-16093. The correlations, based on data means and transformed means, are found in Table 17.

TABLE 17. CORRELATIONS BETWEEN GROUND TRUTH AND LANDSAT-1 MSS DATA (COLORS AND COLOR RATIOS) FOR 20 LAKES IN FRAMES 1017-16091 AND 16093.

	PC1	CHLA	LNCHLA	SECCHI	LNSECCHI
GRN	0.518	0.812	0.718	-0.623	-0.662
RED	0.722	0.888	0.860	-0.788	-0.857
IR1	0.807	0.899	0.886	-0.741	-0.866
IR2	0.589	0.680	0.696	-0.492	-0.642
GRNRED	-0.823	-0.821	-0.886	0.865	0.919
GRNIR1	-0.806	-0.777	-0.838	0.685	0.803
GRNIR2	-0.470	-0.442	-0.521	0.357	0.476
REDIR1	-0.544	-0.476	-0.505	0.274	0.430
REDIR2	-0.026	0.028	-0.017	-0.156	-0.042
IR1IR2	0.516	0.522	0.474	-0.527	-0.507

Several multiple regression models were developed to predict Secchi disc transparency using MSS colors and color ratios as the independent variables. The use of color ratios as independent variables has appeal because the use of ratios tends to normalize the data by removing the brightness components. The best model, as measured by the magnitude of its coefficient of multiple determination (R^2) and standard error of estimate, for estimating Secchi disc transparency is:

$$\widehat{\mathrm{LNSECCHI}} = 0.784 + 2.638\ \mathrm{GRNIR1} - 3.731\ \mathrm{REDIR1} - 0.754\ \mathrm{IR1IR2}$$

The model explains approximately 87 percent of the variance about the mean (Table 18). The observed and predicted Secchi disc transparency values for the 20 lakes are given in Table 19. Although the number of observations is limited (N = 20) and the ground truth is sparse, it is apparent that the LANDSAT-1 MSS can be used to estimate Secchi disc transparency in freshwater lakes.

The most glaring disparity occurs with Middle Lake. Several factors may individually or collectively account for the large residual, including: bottom effects, presence of extensive beds of aquatic macrophytes, the overlap of lake pixels onto land, or some still unsuspected factor. Middle Lake has good water clarity, is relatively shallow, and does have a problem with submerged aquatic macrophytes.

An effort was made to estimate the Secchi disc transparency of 11 Minnesota lakes found in Frame 1022-16373. The regression model, found in subappendix D5, must be viewed with caution because the ground truth was collected approximately two and one-half weeks after the date of LANDSAT-1 coverage. Lakes are dynamic and significant changes may have occurred during the intervening period.

Chlorophyll *a* Estimation

Bressette and Lear (1973), using an infrared photographic technique, have detected algal blooms (primarily *Anacystis*) in the "salt wedge" area of the Potomac River near Maryland Point. The inherent characteristics of the spectral reflectance curve for chlorophyll-bearing plants (Figure 32) were used to advantage. The reflectance of the chlorophyll-bearing plants varies greatly as illustrated by the curve with an abrupt increase at about 700 nanometers. Although the water tends to attenuate the infrared energy in a relatively short distance, the magnitude of the plant reflectance in the near-infrared allows the detection of chlorophyll-bearing plants on or near the water surface. Bressett and Lear (1973) proposed that "it is also probable that the magnitude of the reflected solar energy in the NIR will also depend upon the concentration of phytoplankton in the water..." and demonstrated their infrared technique for the mapping of chlorophyll *a* concentrations.

An examination of the correlations between the MSS data (colors and color ratios) and the chlorophyll *a* data from the 20 NES-sampled lakes (Table 17) suggests that it may be possible to estimate mean chlorophyll *a** levels using the MSS data.

A multiple regression analysis yielded the model:

$$\widehat{\text{LNCHLA}} = 6.905 - 3.662\ \text{GRNIR1} + 0.636\ \text{GRNIR2}$$

---

* Mean value for each lake as determined from ground truth acquired on a specific date.

TABLE 18. ANALYSIS OF VARIANCE TABLE OF A REGRESSION MODEL FOR THE PREDICTION OF SECCHI DISC TRANSPARENCY[a]

Source	Analysis of Variance			
	df	Sum of Squares	Mean Square	Calculated F
Total (corrected)	19	16.340	0.860	
Regression	3	14.152	4.717	34.431
Residual	16	2.188	0.137	

[a] The model was developed using MSS data from Frames 1017-16091 and 1017-16093.

TABLE 19. SECCHI DISC TRANSPARENCY RESIDUALS[a]

Lake Name	Serial Number	SECCHI (m)	$\widehat{\text{SECCHI}}$ (m)	$\text{SECCHI}-\widehat{\text{SECCHI}}$ (m)
Poygan	47	0.46	0.55	-0.09
Butte des Morts	48	0.52	0.48	0.04
Winnebago	49	0.71	0.51	0.20
Green	51	5.69	4.87	0.82
Beaver Dam	53	0.38	0.58	-0.20
Kegonsa	54	0.99	0.55	0.44
Rock	55	2.39	2.68	-0.29
Koshkonong	56	0.32	0.35	-0.03
Lac la Belle	57	1.91	1.42	0.49
Oconomowoc	58	3.51	3.27	0.24
Okauchee	59	1.83	0.64	1.19
Pine	60	3.05	4.85	-1.80
Nagawicka	61	0.91	1.03	-0.12
Pewaukee	62	1.82	1.18	0.64
Tichigan	63	0.57	0.70	-0.13
Browns	64	2.13	1.97	0.26
Middle	65	5.18	2.57	2.61
Delavan	66	0.58	1.07	-0.49
Como	67	0.41	0.55	-0.14
Geneva	68	3.37	4.53	-1.16

[a] The model was developed using MSS data from Frames 1017-16091 and 1017-16093.

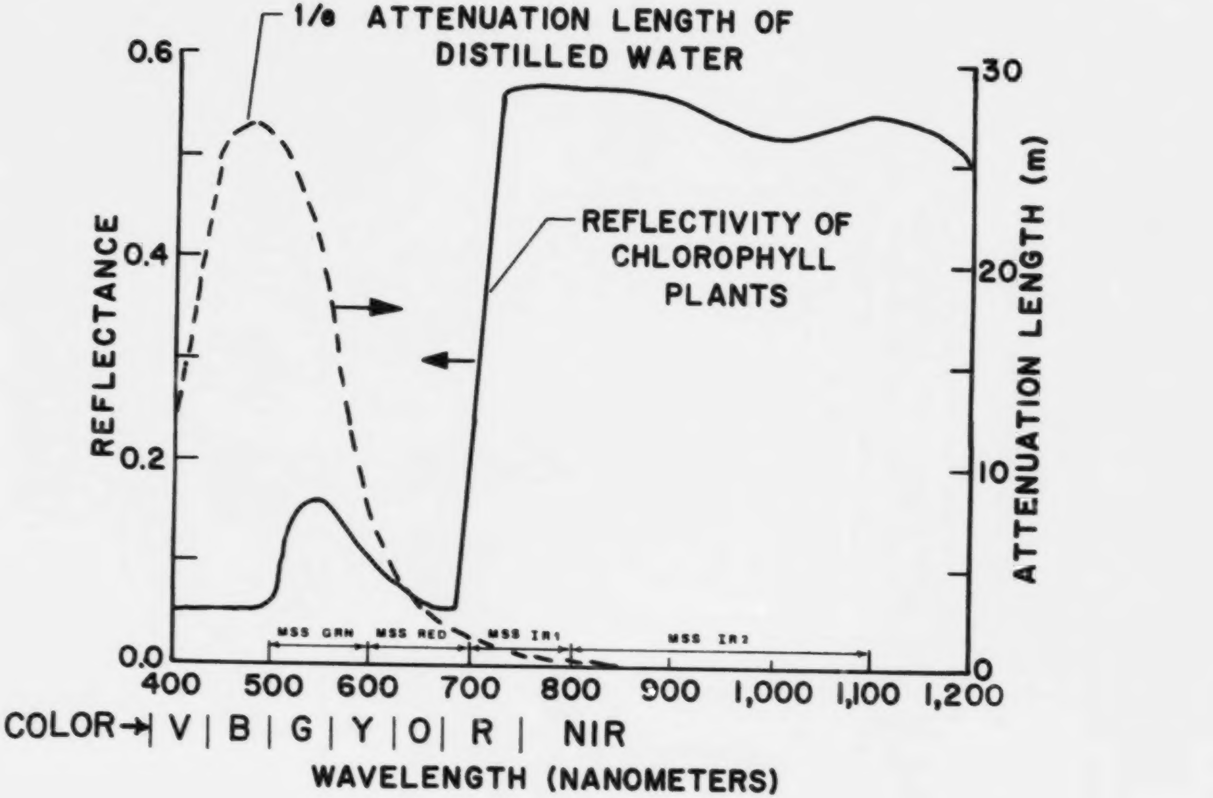


Figure 32. Comparison of the reflectance of chlorophyll-containing plants with the attenuation length of sunlight in distilled water. From Bressette and Lear (1973). The attenuation curve is based on Spiess (1970) and the plant reflectivity curve on Katzoff (1962).

The model explains about 83 percent of the variance about the mean (Table 20). The observed and predicted chlorophyll *a* values, along with their residuals, are found in Table 21. Although the model is purported to estimate chlorophyll *a*, caution must be exercised in assuming that the model is applicable to other lakes or even to the same 20 lakes on a different date. The spectral and spatial resolution of the scanner is low and many factors influence the signal returned to it.

In this case a strong inverse correlation exists between the trophic indicators LNSECCHI and LNCHLA (-0.012) and some percentage of the return signal detected by the multispectral scanner is undoubtly due to the presence of chlorophyll-bearing plants. However, the impact of different types and concentrations of inorganic suspenoids on the chlorophyll *a* are not known at this time. The estimates of chlorophyll *a* derived from the regression model are more properly treated as index numbers than as absolute values.

TABLE 20. ANALYSIS OF VARIANCE TABLE OF A REGRESSION MODEL FOR THE PREDICTION OF CHLOROPHYLL A LEVELS[a]

Source	Analysis of Variance			
	df	Sum of Squares	Mean Square	Calculated F
Total (corrected)	19	23.998	1.263	
Regression	2	19.876	9.938	40.897
Residual	17	4.123	0.243	

[a] The model was developed using MSS data from Frames 1017-16091 and 1017-16093.

TABLE 21. CHLOROPHYLL A RESIDUALS[a]

Lake Name	Serial Number	CHLA (μg/l)	$\widehat{\text{CHLA}}$ (μg/l)	CHLA-$\widehat{\text{CHLA}}$ (μg/l)
Poygan	47	29.7	17.0	12.7
Butte des Morts	48	26.5	29.9	- 3.4
Winnebago	49	27.2	33.7	- 6.5
Green	51	0.8	2.4	- 1.6
Beaver Dam	53	14.1	26.0	-11.9
Kegonsa	54	26.9	24.4	2.5
Rock	55	4.8	3.7	1.1
Koshkonong	56	23.0	41.3	-18.3
Lac la Belle	57	4.9	3.5	1.4
Oconomowoc	58	1.5	2.2	- 0.7
Okauchee	59	4.1	3.9	0.2
Pine	60	3.8	2.1	1.7
Nagawicka	61	13.5	9.0	4.5
Pewaukee	62	6.9	8.9	- 2.0
Tichigan	63	20.5	19.0	1.5
Browns	64	5.1	5.5	- 0.4
Middle	65	4.1	5.5	- 1.4
Delavan	66	30.3	16.9	13.4
Como	67	29.1	14.1	15.0
Geneva	68	2.1	2.2	- 0.1

[a] The model was developed using MSS data from Frames 1017-16091 and 1017-16093.

SECTION VII

LAKE CLASSIFICATION USING LANDSAT-1 MSS DATA

General relationships between MSS data and the trophic state of NES-sampled lakes, as defined by lake position on the first principal component axis (PC1 value), are examined in this section using regression analysis, three-dimensional color ratio models, and color-enhanced photographic products generated through automatic classificatory techniques.

LANDSAT-1 MSS data recorded on 12 different dates (Table 14) were examined in this investigation. Although the temporal coverage of the NES-sampled lakes (Table 15) is fragmentary, a relatively coherent time series exists for 20 lakes in eastern-southeastern Wisconsin. This section will focus on the MSS frames obtained from the Wisconsin area on three occasions (9 August 1972, 11 June 1973, and 17 July 1973). Reference will be made to the other MSS coverage dates and frames which have been largely relegated to Appendix D.

TROPHIC STATE INDEX PREDICTION USING ERTS-1 MSS DATA

As was discussed in Section IV, trophic state is a multi-dimensional concept and can not be adequately assessed by measuring any single indicator. With this in mind, 100 NES-sampled lakes were subjected to the multivariate technique of principal component analysis using LN transformed measurements of six trophic state indicators (LNISEC, LNCHLA, LNTPHOS, LNCOND, LNAAY, LNTON). The position of each lake on the first principal component axis, the PC1 value, is purported to be a trophic state index. The larger the PC1 value, the closer the water body is to the eutrophic end of the scale and, conversely, the smaller the PC1 value, the closer the lake is to the oligotrophic end of the scale.

In Section VI the utility of using the LANDSAT-1 MSS data for the prediction of Secchi disc transparency and chlorophyll a levels was examined. While the estimation of specific trophic indicators is of value, the question arises, "Can the position of a lake on the first principal component axis be predicted using MSS data?"

Investigations relating to lake appearance as related to trophic status (Section VI) support the premise that the multitude of interactions occuring within a lake give the lake volume reflectance an intensity and spectral curve which is indicative of its trophic state. While it can be argued that the MSS lacks the spectral resolution to detect some of the variables incorporated into the trophic state index (such as conductivity and total phosphorus), the elimination of the variables would make the index less stable and therefore more susceptible to a large deviation from normal for a given indicator.

PC1-MSS Regression Analyses

The Wisconsin MSS frames are treated in chronological order starting with those collected on 9 August 1972. Regression models are developed for the prediction of the trophic state index (PC1) values for 20 NES-sampled lakes for each sampling date and then for the same lakes on the basis of mean MSS values for the three dates of LANDSAT-1 coverage.

The product-moment correlation coefficients between the PC1 values for the 20 Wisconsin lakes and the MSS data (colors and color ratios) extracted from MSS frames recorded on the three MSS sampling dates are found in Table 22. The correlations of 9 August 1972 and 17 July 1973 are of similar magnitudes.

TABLE 22. CORRELATIONS BETWEEN LANDSAT-1 MSS DATA (COLORS AND COLOR RATIOS) COLLECTED ON THREE DATES AND THE TROPHIC STATUS OF 20 WISCONSIN LAKES

MSS Colors and Ratios	Date of LANDSAT-1 Flyover 9 August 1972	 11 June 1973	 17 July 1973
GRN	0.518	0.151	0.479
RED	0.722	0.533	0.721
IR1	0.807	0.512	0.836
IR2	0.589	0.174	0.628
GRNRED	-0.823	-0.712	-0.749
GRNIR1	-0.806	-0.540	-0.820
GRNIR2	-0.470	-0.091	-0.485
REDIR1	-0.544	0.084	-0.422
REDIR2	-0.026	0.298	0.109
IR1IR2	0.516	0.445	0.479

Numerous regression models were developed during the investigation; only the "best" models are presented in this report. Criteria used in the selection of the "best" models included the magnitude of the coefficient of multiple determination (R^2) and the standard error of estimate. All regression coefficients were required to be significant at the 0.05 level.

The best regression model for the prediction of the trophic state index (PC1) values of the 20 Wisconsin lakes for 9 August 1972 is:

$$\widehat{PC1} = 7.682 - 6.074\ GRNIR1 + 1.155\ GRNIR2$$

The model explains about 81 percent of the variance about the mean and has a standard error (s.e.) of estimate of 0.840 (Table 23).

TABLE 23. ANALYSIS OF VARIANCE TABLE OF A REGRESSION MODEL FOR THE PREDICTION OF THE TROPHIC STATUS OF 20 WISCONSIN LAKES FOUND IN LANDSAT-1 MSS FRAMES 1017-16091 AND 1017-16093 (9 AUGUST 1972)

	Analysis of Variance			
Source	df	Sum of Squares	Mean Square	Calculated F
Total (corrected)	19	62.555	3.292	
Regression	2	50.572	25.286	35.867
Residual	17	11.983	0.705	

R^2 = 0.8084 x 100 = 80.84%   s.e. of estimate = 0.840

When considering the R^2 value of the above model it must be kept in mind that the PC1 was developed using mean values of the ground truth measurements taken on three occasions during the 1972 open water season. The MSS data were collected within a few seconds on 9 August 1972.

An examination of the residuals ($PC1-\widehat{PC1}$) in Table 24 reveals relatively large absolute values for Middle, Tichigan, Pine, Beaver Dam, and Butte des Morts. Middle Lake and Butte des Morts are predicted to be in worse condition (closer to the eutrophic end of the scale) than their PC1 values indicate. The other three lakes are estimated to be in better condition (closer to the oligotrophic end of the scale) than their PC1 values suggest. The model produced poor results when it was used to predict the trophic state index values of lakes in other MSS frames.

A regression model was developed for the same 20 Wisconsin lakes using MSS data collected by the LANDSAT-1 on 11 June 1973. The model:

$$\widehat{PC1} = 42.761 - 18.423\ GRNRED - 18.948\ REDIR1 + 3.057\ GRNIR2$$

explains about 70 percent of the variation about the mean and has a

TABLE 24. TROPHIC STATE INDEX (PC1) RESIDUALS OF 20 WISCONSIN LAKES FOUND IN LANDSAT-1 MSS Frames 1017-16091 AND 1017-16093 (9 AUGUST 1972)

Lake Name	Serial Number	PC1	$\widehat{PC1}$	PC1-$\widehat{PC1}$
Poygan	47	1.68	1.41	0.27
Butte des Morts	48	1.27	2.39	-1.12
Winnebago	49	2.36	2.70	-0.34
Green	51	-1.67	-1.53	-0.14
Beaver Dam	53	3.29	2.14	1.15
Kegonsa	54	1.48	2.13	-0.65
Rock	55	-1.21	-0.85	-0.36
Koshkonong	56	2.45	2.87	-0.42
Lac la Belle	57	-1.43	-0.94	-0.49
Oconomowoc	58	-1.82	-1.82	0.00
Okauchee	59	-0.62	-0.89	0.27
Pine	60	-0.71	-1.88	1.17
Nagawicka	61	1.27	0.58	0.69
Pewaukee	62	0.59	0.45	0.14
Tichigan	63	3.11	1.51	1.60
Browns	64	-1.07	-0.43	-0.64
Middle	65	-2.29	-0.56	-1.73
Delavan	66	2.03	1.46	0.57
Como	67	1.15	1.18	-0.03
Geneva	68	-1.71	-1.78	0.06

standard error of estimate of 1.087 (Table 25). The residuals are are displayed in Table 26. The model has less practical value for the prediction of trophic state than the PC1 model for 9 August 1972.

The MSS data collected on 17 July 1973 were also used to develop a regression model for the prediction of the PC1 values for the same lakes with the results:

$$\widehat{PC1} = 140.430 - 9.375\ \text{GRNRED} - 98.913\ \text{REDIR1} + 45.672\ \text{REDIR2} - 57.330\ \text{IR1IR2}$$

This model explains about 81% of the variance about the mean and has a standard error of estimate of 0.892 (Table 27). The residuals are displayed in Table 28.

Each date of LANDSAT-1 coverage has its unique model for the prediction of the trophic state of the 20 lakes.

TABLE 25. ANALYSIS OF VARIANCE TABLE OF A REGRESSION MODEL FOR THE PREDICTION OF THE TROPHIC STATUS OF 20 WISCONSIN LAKES FOUND IN LANDSAT-1 MSS Frames 1323-16194 AND 1323-16100 (11 June 1973)

		Analysis of Variance		
Source	df	Sum of Squares	Mean Square	Calculated F
Total (corrected)	19	62.555	3.292	
Regression	3	43.649	14.550	12.313
Residual	16	18.906	1.182	

R^2 = 0.6978 x 100 = 69.78% s.e. of estimate = 1.087

TABLE 26. TROPHIC STATE INDEX (PC1) RESIDUALS OF 20 WISCONSIN LAKES FOUND IN LANDSAT-1 MSS Frames 1323-16194 AND 1323-16100 (11 June 1973)

Lake Name	Serial Number	PC1	$\widehat{PC1}$	$PC1-\widehat{PC1}$
Poygan	47	1.68	1.19	0.49
Butte des Morts	48	1.27	1.52	-0.25
Winnebago	49	2.36	1.30	1.06
Green	51	-1.67	-0.45	-1.22
Beaver Dam	53	3.29	3.29	0.00
Kegonsa	54	1.47	0.05	1.42
Rock	55	-1.21	-0.63	-0.58
Koshkonong	56	2.45	3.64	-1.19
Lac la Belle	57	-1.43	-0.11	-1.32
Oconomowoc	58	-1.82	-0.66	-1.16
Okauchee	59	-0.62	-0.36	-0.98
Pine	60	-0.71	-2.16	1.45
Nagawicka	61	1.27	1.10	0.17
Pewaukee	62	0.59	0.55	0.04
Tichigan	63	3.11	1.36	1.75
Browns	64	-1.07	-1.30	0.23
Middle	65	-2.29	-1.22	-1.07
Delavan	66	2.03	0.71	1.32
Como	67	1.15	1.29	-0.14
Geneva	68	-1.71	-1.70	-0.01

TABLE 27. ANALYSIS OF VARIANCE TABLE OF A REGRESSION MODEL FOR THE PREDICTION OF THE TROPHIC STATUS OF 20 WISCONSIN LAKES FOUND IN LANDSAT-1 MSS Frames 1359-16091 AND 1359-16094 (17 July 1973)

		Analysis of Variance		
Source	df	Sum of Squares	Mean Square	Calculated F
Total (corrected)	19	62.555	3.292	
Regression	4	50.631	12.658	15.922
Residual	15	11.925	0.795	

R^2 = 0.8094 x 100 = 80.94%   s.e. of estimate = 0.892

TABLE 28. TROPHIC STATE INDEX (PC1) RESIDUALS OF 20 WISCONSIN LAKES FOUND IN LANDSAT-1 MSS FRAMES 1359-16091 AND 1359-16094 (17 July 1973)

Lake Name	Serial Number	PC1	$\widehat{PC1}$	$PC1-\widehat{PC1}$
Poygan	47	1.68	3.06	-1.38
Butte des Morts	48	1.27	1.76	-0.49
Winnebago	49	2.36	1.73	0.63
Green	51	-1.67	-1.84	0.17
Beaver Dam	53	3.29	2.15	1.14
Kegonsa	54	1.48	0.63	0.85
Rock	55	-1.21	-1.20	-0.01
Koshkonong	56	2.45	3.17	-0.72
Lac la Belle	57	-1.43	-1.48	0.05
Oconomowoc	58	-1.82	-1.15	-0.67
Okauchee	59	-0.62	-0.21	-0.41
Pine	60	-0.71	-1.59	0.88
Nagawicka	61	1.27	0.80	0.47
Pewaukee	62	0.59	0.29	0.30
Tichigan	63	3.11	2.83	0.28
Browns	64	-1.07	-0.49	-0.58
Middle	65	-2.29	-0.52	-1.77
Delavan	66	2.03	0.92	1.11
Como	67	1.15	0.70	0.45
Geneva	68	-1.71	-1.41	-0.30

Although the lake color ratios vary from frame to frame (date to date), it is not unreasonable to expect that over a period of time a lake would present an average color or appearance, which would be more representative of the water body's position on a trophic scale. With this in mind, a new regression model was developed using mean color ratios derived from the three dates of LANDSAT-1 coverage. For example, a lake's mean GRNRED color ratio was determined by establishing its GRNRED ratio for each of the three LANDSAT-1 dates, summing these ratios and dividing by the number of LANDSAT-1 dates. Stated more simply,

$$XGRNRED = (GRNRED_1 + GRNRED_2 + GRNRED_3)/3$$

where XGRNRED is the mean color ratio for a lake, $GRNRED_1$ is the ratio determined for the first LANDSAT-1 date, $GRNRED_2$ is the ratio for the second date of LANDSAT-1 coverage, and $GRNRED_3$ is the ratio for the third date of coverage. The coverage dates are 9 August 1972, 11 June 1973, and 17 July 1973.

The model which best predicts the PC1 values for the 20 lakes is:

$$\widehat{PC1} = 4.127 - 6.623\ XGRNRED - 3.511\ XREDIR2 + 8.040\ XIR1IR2$$

It explains about 80 percent of the variation about the mean and has a standard error of estimate of 0.887 (Table 29). The residuals are displayed in Table 30. Relatively large residuals (absolute values) exist for Middle, Pine, and Butte des Morts. The elimination of the 11 June 1973 data and use of average ratios developed from the two remaining dates (9 August 1972 and 17 July 1973) would result in a better model.

Regression models were also developed for NES-sampled lakes in Minnesota and New York where LANDSAT-1 MSS coverage was available. The best model, as measured by the criteria stated previously, for each date of LANDSAT-1 MSS coverage is displayed in Table 31 along with the models for the Wisconsin lakes.

Although a model is included for all of the LANDSAT-1 MSS coverage dates, except for the two dates with very small sample sizes, some of the models are clearly inadequate. For example, the models with an R^2 less than about 0.80 (80 percent) do not have much predictive value. This effectively eliminates a model for the Wisconsin lakes (11 June 1973) and several models for the Minnesota lakes (6 October 1972, 28 May 1973, 3 July 1973). Another model, 19 August 1972 (New York) is of dubious value because the number of observations is small (N = 7), and there are only four degrees of freedom associated with the residuals.

TABLE 29. ANALYSIS OF VARIANCE TABLE OF A REGRESSION MODEL FOR THE PREDICTION OF THE TROPHIC STATUS OF 20 WISCONSIN LAKES USING MEAN MSS COLOR RATIOS FROM THREE DATES (9 AUGUST 1972, 11 JUNE 1973, 17 JULY 1973)

		Analysis of Variance		
Source	df	Sum of Squares	Mean Square	Calculated F
Total (corrected)	19	62.555	3.292	
Regression	3	50.003	16.676	22.575
Residual	16	12.529	0.783	

$R^2 = 0.7997 \times 100 = 79.97\%$ s.e. of estimate = 0.887

TABLE 30. TROPHIC STATE INDEX (PC1) RESIDUALS OF 20 WISCONSIN LAKES FROM A REGRESSION MODEL INCORPORATING MEAN MSS COLOR RATIOS FROM THREE DATES (9 AUGUST 1972, 11 JUNE 1973, 17 JULY 1973)

Lake Name	Serial Number	PC1	$\widehat{PC1}$	$PC1-\widehat{PC1}$
Poygan	47	1.68	1.66	0.02
Butte des Morts	48	1.27	2.45	-1.18
Winnebago	49	2.36	1.77	0.59
Green	51	-1.67	-1.61	-0.06
Beaver Dam	53	3.29	3.05	0.24
Kegonsa	54	1.48	1.33	0.15
Rock	55	-1.21	-0.93	-0.28
Koshkonong	56	2.45	3.32	-0.87
Lac la Belle	57	-1.43	-1.05	-0.38
Oconomowoc	58	-1.82	-1.23	-0.59
Okauchee	59	-0.62	-0.47	-0.15
Pine	60	-0.71	-1.99	1.28
Nagawicka	61	1.27	0.42	0.85
Pewaukee	62	0.59	0.29	0.30
Tichigan	63	3.11	1.48	1.63
Browns	64	-1.09	-0.69	-0.40
Middle	65	-2.29	-0.36	-1.93
Delavan	66	2.03	1.45	0.58
Como	67	1.15	0.98	0.17
Geneva	68	-1.71	-1.74	0.03

TABLE 31. REGRESSION MODELS DEVELOPED FOR THE ESTIMATION OF TROPHIC STATE USING LANDSAT-1 MSS DATA[a]

Date, Frame(s) and Area	Number of Lakes	Regression Model	R^2 x 100	Standard Error of Estimate	Appendix
9 August 1972 1017-16091 1017-16093 Wisconsin	20	$\widehat{PC1} = 7.682 - 6.074\ \text{GRNIR1} + 1.155\ \text{GRNIR2}$	80.84%	0.840	D1
11 June 1973 1323-16194 1323-16100 Wisconsin	20	$\widehat{PC1} = 42.761 - 18.423\ \text{GRNRED} - 18.948\ \text{REDIR1} + 3.057\ \text{GRNIR1}$	69.78%	1.087	D3
17 July 1973 1359-16091 1359-16094 Wisconsin	20	$\widehat{PC1} = 140.430 - 9.375\ \text{GRNRED} - 98.913\ \text{REDIR1} + 45.672\ \text{REDIR2} - 57.330\ \text{IR1IR2}$	80.94%	0.892	D4
1017-16091 1017-16093 1323-16194 1323-16100 1359-16091 1359-16094	20	$\widehat{PC1} = 4.127 - 6.623\ \text{XGRNRED} - 3.511\ \text{XREDIR2} + 8.040\ \text{XIR1IR2}$	79.97%	0.887	--
14 August 1972 1022-16373 Minnesota	11	$\widehat{PC1} = 13.150 - 10.626\ \text{GRNIR1} + 2.327\ \text{GRNIR2}$	96.06%	0.456	D5

TABLE 31. REGRESSION MODELS FOR THE ESTIMATION OF TROPHIC STATE USING LANDSAT-1 MSS DATA[a] (continued)

Date, Frame(s) and Area	Number of Lakes	Regression Model	R^2 x 100	Standard Error of Estimate	Appendix
6 October 1972 1075-16321 Minnesota	12	$\widehat{PC1}$ = 11.533 - 7.132 REDIR1	43.91%	1.540	D6
8 October 1972 1077-16431 Minnesota	7	$\widehat{PC1}$ = 35.509 - 18.548 GRNRED	95.12%	0.247	D7
28 May 1973 1309-16325 Minnesota	11	$\widehat{PC1}$ = -16.537 + 9.844 IR1IR2	49.33%	1.525	D8
3 July 1973 1345-16322 Minnesota	12	$\widehat{PC1}$ = 10.544 - 7.240 REDIR1	70.09%	1.117	D9
4 July 1973 1346-16381 Minnesota	7	$\widehat{PC1}$ = 11.715 - 8.277 REDIR1	92.34%	0.669	D10
19 August 1972 1027-15233 New York	7	$\widehat{PC1}$ = -4.891 - 8.805 GRNIR1 + 19.301 REDIR1	82.82%	0.740	D11

---

[a] Regression models were not constructed for Frames 1036-16152 (28 August 1972, Wisconsin) and 1080-15180 (11 October 1972, New York) due to the relatively small number of observations.

An examination of the remaining models indicates that they all differ from one another. Attempts to predict the PC1 values for a particular LANDSAT-1 coverage date, using a model from another date, produced statistically insignificant results.

Although their regression coefficients are different, some models have the same variables in common. For example, the 9 August 1972 (Wisconsin) model and the 14 August 1972 (Minnesota) model incorporate the variables GRNIR1 and GRNIR2. Both models have an R^2 exceeding 0.80 and are of value in predicting the PC1 values of water bodies contained in their respective frames.

The models for 3 July 1973 (Minnesota) and 4 July 1973 (Minnesota) contain a single independent variable, IR1. Yet, the first model has an R^2 of about 70 percent and the latter model an R^2 of about 92 percent. Some of the lakes are common to both models. An attempt to use the 4 July 1973 model to predict the PC1 values of the NES lakes in the 3 July 1973 frame drew statistically insignificant results.

The degree of success in the prediction of lake trophic state, as defined by a lake's position on the first principal component axis, varies considerably from date to date. Several factors could account for the variability.

Lakes are, by their very nature, dynamic and can change significantly in appearance over a matter of days or weeks. Algal blooms, the growth of aquatic macrophytes, the influx of silt carried by rain-swollen streams, and, in the case of shallow lakes with sufficient fetch, sediments churned up by wind-induced turbulence can produce changes in the volume reflectance detectable by both human observers and other sensors such as the MSS. Super-imposed on the variations associated with lake dynamics are variations related to atmospheric conditions and solar angle.

The impact of antecedent precipitation on lake volume reflectance can not be ascertained with any degree of certainty in this study. The relatively poor regression model for the 3 July 1973 (Minnesota) may be a consequence of the heavy rains on 2 July 1973, but this is largely conjecture.

THREE-DIMENSIONAL MSS COLOR RATIO MODELS

In the preceding section, several regression models were developed to predict the trophic status of selected lakes using MSS ratios. The assumptions were made that the PC1 values adequately represent the position of the lakes on a trophic scale and that lake phenomena that correlate with the index are detectable using the MSS.

A less sophisticated but practical approach to evaluating relationships between MSS data and trophic state involves the visual examination of MSS data patterns in light of a general knowledge of the lakes as well as their trophic state index values (PC1). Although this could be done through the use of data matrices, a graphic approach is favored because it is very conducive to pattern detection and interpretation. An examination of the various MSS ratios incorporated into the regression models in Table 31 indicates that the MSS ratios GRNIR1, GRNRED, and REDIR1 might be used to advantage.

The three-dimensional models in this section were produced using the same program and equipment as in the PCA ordination model found in Section IV. The numerals inside the "ball" are the lake's serial number and those near the lake's name represent its PC1 value. Lakes with a serial number greater than 100 fell outside the scope of the PCA ordination and therefore lack a PC1 value. Although a MSS color ratio model was developed for each date of LANDSAT-1 coverage, the Wisconsin lakes will serve as a focal point. The other models are found in Appendix D.

The color ratio model for 9 August 1972 (Wisconsin: 1017-16091, 1017-16093) is found in Figure 33. The model can be examined using both a general knowledge acquired about the lakes and their PC1 values as guides. There is a very definite trend for the color ratios to increase as one moves from lakes considered to be located near the eutrophic end of the scale (e.g., Beaver Dam) toward those situated more closely to the oligotrophic end (e.g., Green, 51).

It is unrealistic to expect complete agreement between the position of the lakes in the color ratio model and their respective PC1 values. In addition to the problems created by the dynamic nature of the lakes, some additional uncertainty is generated by the sampling methods. The lake MSS data for the three-dimension model were acquired by sensing the lake body, at least to Secchi depth (or to the bottom if the Secchi depth is greater than the water depth), on a pixel-by-pixel basis. The PC1 values were derived from ground truth collected at selected points (stations) ranging in number from one (e.g., Middle Lake) to nine (Lake Winnebago). As will be seen in the next section, the number of sampling sites and their location on a lake can have a significant effect on the lake's trophic index value. In addition, the sensor data represent lake phenomena at a single point in time; the PC1 values were derived using annual mean values.

Assuming that the PC1 value of Middle Lake is representative of its trophic state, it is "out of position" relative to the other lakes in the 9 August 1972 model. The lake's color ratio coordinates are indicative of a lake situated more closely to the eutrophic end of the trophic scale. Several factors may be responsible for this apparent misclassification.

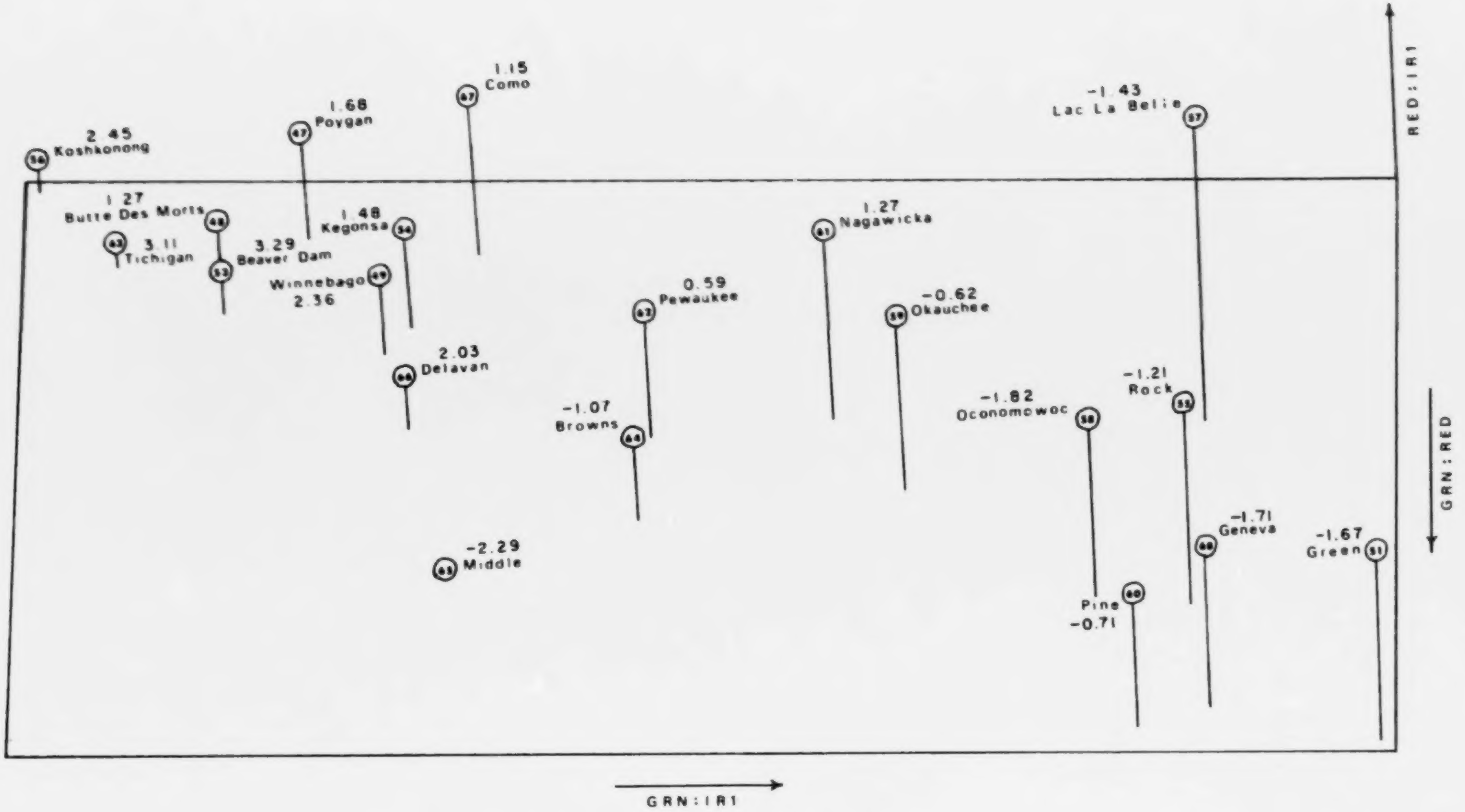


Figure 33. Three-dimensional color ratio model for 9 August 1972. The 20 Wisconsin lakes were extracted from LANDSAT-1 MSS Frames 1017-16093 and 1017-16091. The frames are in juxtaposition on the same flight line.

As discussed previously, the trophic scale does not directly incorporate the extent of aquatic macrophytes and algal organisms in the lakes, nor does it include a direct measure of lake morphometry. The sensor may very well be "seeing" large masses of plants and/or the lake bottom. Middle Lake is known to have weed problems and it has extensive shallows. The incorporation of some direct measure of aquatic weeds into the trophic state index would shift Middle Lake toward the eutrophic end of the scale and bring the lake index value in closer agreement with the lake's coordinates in the color ratio model.

The 11 June 1973 model of the same 20 lakes is shown in Figure 34 along with three other lakes (Mendota, Monona, and Waubesa). Many of the lakes have shifted their position significantly (e.g., Winnebago, Kegonsa, Geneva, Rock, and Oconomowoc). The color ratio-trophic state relationships so evident in the three-dimensional model of 9 August 1972 are not as obvious in 11 June 1973. Efforts to develop a regression model, using the PC1 values as the dependent variable in the preceding section, yielded statistically insignificant results.

The Wisconsin lakes are incorporated into a three-dimensional color ratio model using MSS data from 17 July 1973 (Figure 35). Although not identical in all respects, the model bears a marked resemblence to the 9 August 1972 model. The positional change of Lake Poygan may be due in part to the large portion of cloud coverage (approximately 50 percent).

The model in Figure 36 represents the mean color ratio relationships among the 20 Wisconsin lakes using the MSS data for three dates (9 August 1972, 11 June 1973, 17 July 1973). The mean ratios were determined in the previous section. The model may be thought of as a representation of the general appearance of the lakes. A more extended time series is desirable, but cloud cover and poor quality MSS bands have made this impossible despite the 18-day repetitive coverage cycle.

A three-dimensional color ratio model was constructed for each of the remaining dates of LANDSAT-1 MSS coverage (Table 15). The models are found in Appendix D. It will be noted in some of the models of Minnesota lakes (14 August 1972, 6 October 1972, 8 October 1972) that certain lakes (Wagonga, Silver) are isolated from the other lakes. These lakes have IR1 DN values which exceed their respective RED DN values. The lakes are at the extreme end of the trophic scale and are sometimes referred to as being hypereutrophic.

An examination of both the three-dimensional color ratio models and their associated regression models suggests that the utility of the MSS for the estimation of trophic state is dependent to a substantial degree upon the time of year. The Wisconsin and Minnesota frames recorded relatively early during the open water season (28 May 1973,

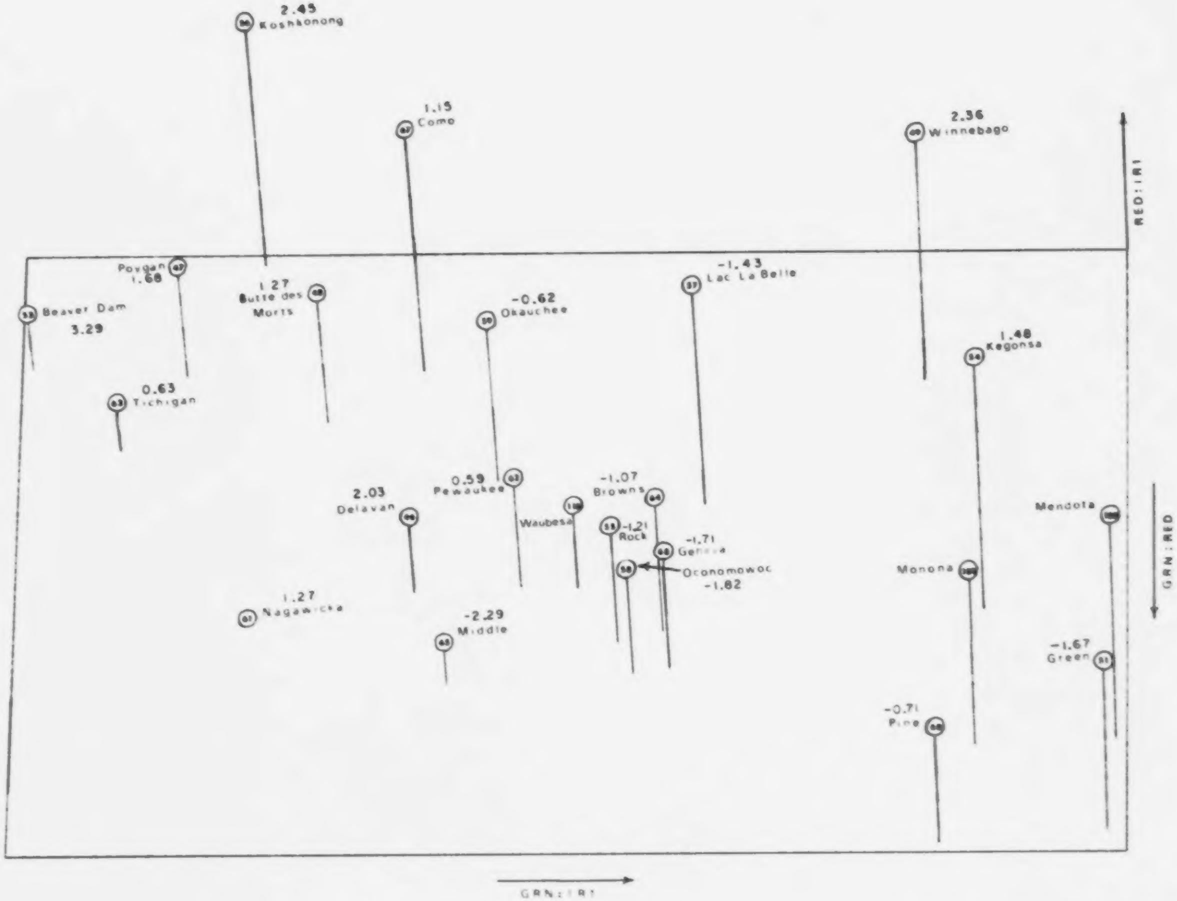


Figure 34. Three-dimensional color ratio model for 11 June 1973. The 23 Wisconsin lakes were extracted from LANDSAT-1 MSS Frame 1323-16100. Three of the lakes (Mendota, Monona, and Waubesa) fall outside the scope of the investigation, but are included because they are well-known by lake scientists.

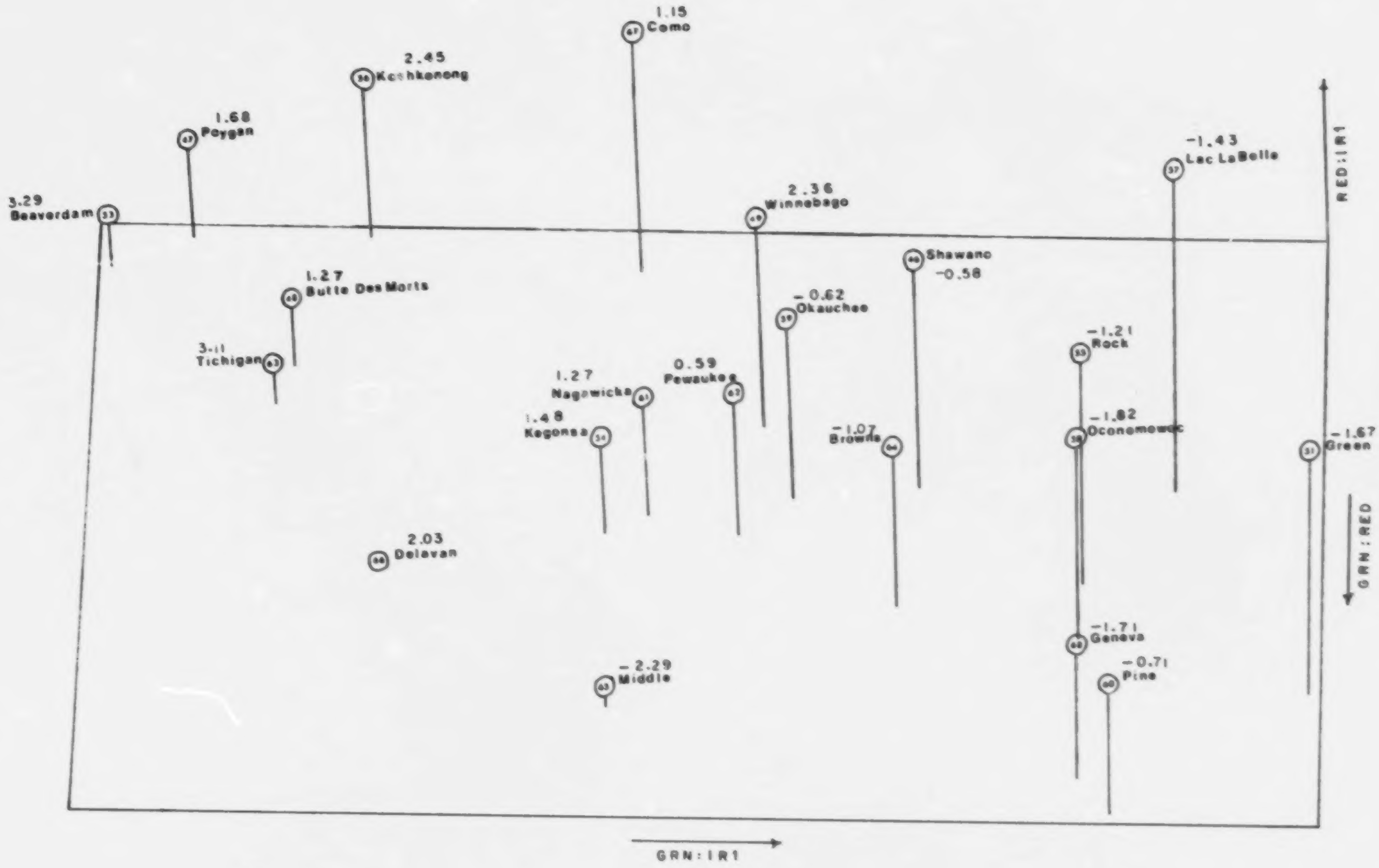


Figure 35. Three-dimensional color ratio model for 17 July 1973. The 20 Wisconsin lakes were extracted from LANDSAT-1 MSS Frames 1359-16091 and 1359-16094.

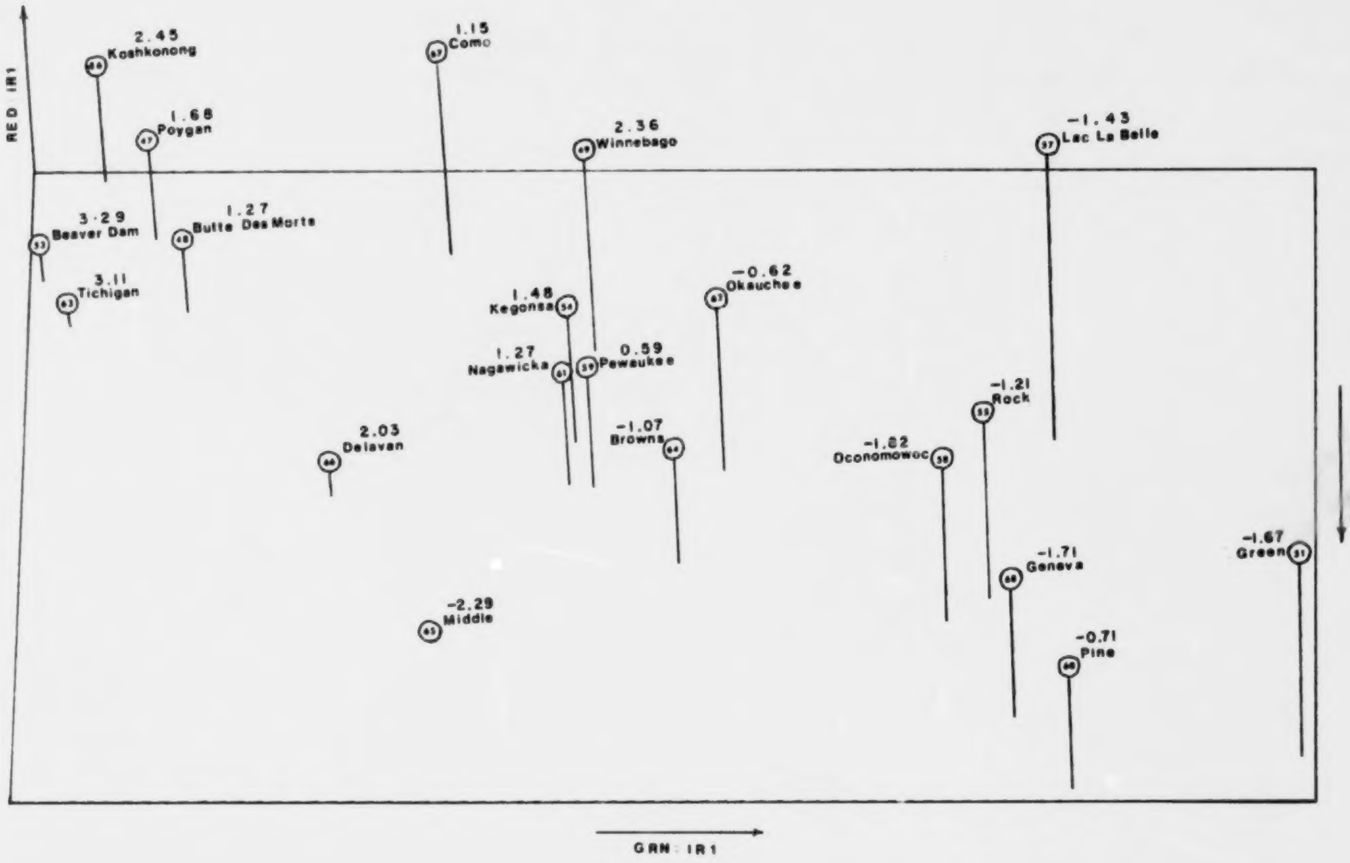


Figure 36. Three-dimensional color ratio model for three dates of LANDSAT-1 MSS coverage (9 August 1972, 11 June 1973, 17 July 1973). The model was developed using mean color ratios derived from MSS data collected on the three dates.

11 June 1973) have spectral curves which correlate poorly with the lake PC1 values. The correlations are much stronger in the case of MSS frames recorded later in the season (9 August 1972, 14 August 1972, 17 July 1973, 8 October 1972) when the contrast between lakes at different points on the trophic scale tend to be at a maximum.

LAKE CLASSIFICATION USING MSS DATA IN CONJUNCTION WITH AN AUTOMATIC DATA PROCESSING TECHNIQUE

Up to this point the lake MSS data have been examined using regression techniques and three-dimensional color ratio models. The investigations were undertaken using mean color values and mean color ratios for each LANDSAT-1 date. The lakes were treated as entities without regard to differences which might be present within them. Automatic data processing techniques are well-suited, not only for classifying lakes, but also for classifying different types of water within individual lakes (Boland, 1975; Boland and Blackwell, 1975).

It is becoming increasingly common to use automatic data processing (ADP) techniques in remote sensing studies (e.g., Hoffer, et al., 1972). ADP techniques merit consideration because they permit the reduction of large masses of data in realistic time periods and add objectivity to the classificatory process.

With the advantages of ADP in mind, an effort was undertaken by Blackwell (1974, personal communication) to apply the techniques to the 20 lakes found in MSS Frames 1017-16091 and 1017-16093 (9 August 1972). The equipment and software at the JPL/IPL were used to process the MSS data reported here and produce hard copy in the form of black and white photographs and color-enhanced prints. The methodology employed is briefly described below.

Utilizing a LARS-developed (Laboratory for Applications of Remote Sensing, Purdue University) spectral pattern-recognition-algorithm, the IPL IBM 360/44 was trained using the GRN, RED, and IR1 MSS data in conjunction with the lake PC1 values. Preliminary processing indicated that the IR2 band data would be of little value in distinguishing one lake from another or one area of a lake from another area of the same water body. The IR2 data were not included, thereby reducing the amount of CPU time required for classification.

The number of spectral classes was set by establishing one class for each different PC1 value among the 20 Wisconsin lakes. This resulted in the formation of 19 different classes (Table 32). Butte des Morts and Nagawicka have the same PC1 value and were assigned to the same class. The computer was statistically trained to recognize each lake as belonging to a particular class. For example, the computer was trained to perceive Beaver Dam Lake as belonging to Class 1, Tichigan as Class 2, ..., Middle Lake as Class 19. Each pixel in the 20 lakes was then classified by the computer into one of the 19 classes. The results of the classification procedure are found in Table 33.

TABLE 32. LAKE TROPHIC STATE INDEX CLASS ASSIGNMENTS FOR THE ADP TECHNIQUE

Lake Name	Serial Number	PC1 Value	Computer Trained to Recognize as Class:
Beaver Dam	53	3.29	1
Tichigan	63	3.11	2
Koshkonong	56	2.45	3
Winnebago	49	2.36	4
Delavan	66	2.03	5
Poygan	47	1.68	6
Kegonsa	54	1.48	7
Butte des Morts	48	1.27	8
Nagawicka	61	1.27	8
Como	67	1.15	9
Pewaukee	62	0.59	10
Okauchee	59	-0.62	11
Pine	60	-0.71	12
Browns	64	-1.07	13
Rock	55	-1.21	14
Lac la Belle	57	-1.43	15
Green	51	-1.67	16
Geneva	68	-1.71	17
Oconomowoc	58	-1.82	18
Middle	65	-2.29	19

All of the pixels in a homogeneous lake would be classified as falling into the class for which the lake served as a training area. It is very unlikely to find a lake that has the same trophic characteristics throughout its areal extent. Some indication of the heterogeneous nature of the 20 Wisconsin lakes may be obtained by examining Table 33. Beaver Dam Lake, for example, has 69.4 percent of its pixels classified as belonging to Class 1, 10 percent to Class 2, ..., and 1.3 percent to Class 7. Lake Kegonsa exhibits the least heterogeneity with 87.4 percent of its pixels falling in Class 7. The percentages expressed here should be treated as approximations because the "sixth line" banding affects the results of any such classification scheme. If the classificatory results had indicated homogeneous conditions in each lake,

TABLE 33. ADP RESULTS FOR 9 AUGUST 1972 USING A 19 CLASS CLASSIFICATION[a]

Lake Name	Serial Number	PC1 Value	Trained as Class:	Six Major Classes Found in the Lake (Percentage)					
Beaver Dam	53	3.29	1	1 (69.4)	10 (13.0)	2 (9.8)	19 (3.2)	4 (2.5)	7 (1.3)
Tichigan	63	3.11	2	2 (41.6)	5 (17.0)	1 (16.3)	4 (8.5)	8 (8.5)	7 (3.9)
Koshkonong	56	2.45	3	7 (44.5)	17 (12.6)	16 (6.0)	12 (5.1)	2 (4.8)	3 (4.7)
Winnebago	49	2.36	4	4 (18.0)	10 (16.3)	5 (13.8)	2 (9.8)	7 (9.5)	1 (9.1)
Delavan	66	2.03	5	5 (66.0)	3 (8.0)	8 (6.1)	7 (4.2)	1 (4.0)	2 (3.5)
Poygan	47	1.68	6	7 (24.0)	6 (18.3)	9 (13.4)	8 (10.1)	5 (8.0)	4 (6.7)
Kegonsa	54	1.48	7	7 (87.4)	9 (7.4)	6 (3.0)	3 (1.2)	2 (0.1)	1 (0.1)
Butte des Morts	48	1.27	8	2 (29.3)	8 (23.3)	5 (18.4)	9 (7.8)	3 (7.0)	6 (5.8)
Nagawicka	61	1.27	8	15 (41.3)	10 (16.5)	5 (9.3)	4 (8.3)	17 (6.0)	1 (5.0)
Como	67	1.15	9	7 (39.1)	9 (31.2)	1 (7.5)	2 (5.0)	4 (3.4)	8 (3.4)
Pewaukee	62	0.59	10	10 (35.0)	14 (14.9)	1 (13.0)	11 (8.9)	13 (5.2)	19 (5.2)
Okauchee	59	-0.62	11	11 (32.7)	16 (19.5)	14 (13.0)	10 (11.8)	1 (6.6)	12 (5.8)
Pine	60	-0.71	12	12 (35.9)	16 (30.9)	11 (4.6)	17 (4.1)	19 (4.1)	13 (3.7)

TABLE 33. ADP RESULTS FOR 9 AUGUST 1972 USING A 19 CLASS CLASSIFICATION[a] (continued)

Lake Name	Serial Number	PC1 Value	Trained as Class:	Six Major Classes Found in the Lake (Percentage)					
Browns	64	-1.07	13	11 (22.0)	13 (17.1)	19 (15.5)	12 (10.0)	16 (6.5)	1 (6.1)
Rock	55	-1.21	14	16 (31.1)	12 (15.6)	14 (12.7)	11 (12.5)	15 (9.9)	17 (4.6)
Lac la Belle	57	-1.43	15	15 (43.0)	10 (11.9)	14 (11.8)	7 (5.3)	5 (4.9)	11 (4.8)
Green	51	-1.67	16	16 (45.0)	12 (27.8)	14 (7.7)	17 (5.7)	11 (5.2)	2 (1.9)
Geneva	68	-1.61	17	17 (38.0)	16 (18.3)	12 (15.6)	14 (12.7)	18 (5.4)	10 (2.3)
Oconomowoc	58	-1.82	18	16 (23.6)	12 (19.2)	14 (12.4)	17 (9.4)	15 (8.7)	11 (7.9)
Middle	65	-2.29	19	12 (22.2)	19 (15.4)	13 (12.8)	1 (11.1)	11 (10.2)	16 (10.2)

[a] The six trophic classes listed for each lake were assigned most of the pixels representing the lake. The percentage of pixels assigned to each class is given in parentheses.

the analysis could stop at this point. However, this is not the case, and the question arises: "What trophic-related patterns exist in each lake?" This necessitates the development of some sort of imagery.

Images of the machine-classified lakes can be produced in the form of line printer copy using different symbols to represent the various trophic classes and also as photographic prints and transparencies. Output in the form of photographs was selected because they are compact, easily handled, have much greater resolution than line printer copy of equal size, and are readily interpretable, particularly when in color.

The ADP-classified lakes (9 August 1972) are displayed in Figure 37 using 19 gray-levels, one for each class. Class 1 is located toward the eutrophic end of the trophic scale (black) and Class 19 (white) is toward the oligotrophic end. It would be incorrect to call a Class 19 pixel or lake oligotrophic because none of the lakes examined are considered to possess the necessary attributes. The pronounced linear features are artifacts introduced by a defect in the MSS and are generally referred to as "sixth line" banding. It is important to overlook their presence when studying the patterns present in the lake images.

Figure 38 is a color-enhanced version of the 19-class classification of the 20 lakes (9 August 1972). Black has been assigned to represent Class 1, and each of the remaining 18 classes has been assigned its unique color. The colors were produced by using different ratios of the three primary colors: blue, green, and red. Detailed information regarding the principles involved is found in the work by Committee on Colorimetry (1966).

Differences among and within the lakes are readily apparent. Some of the lakes (Kegonsa and Beaver Dam) present a relatively homogeneous appearance. Others (Winnebago and Poygan) exhibit a diversity of trophic classes. Some of the lakes have features which bear mentioning.

The appendix-like structure which appears attached to the northeast quadrant of Delavan Lake is the entry point of Jackson Creek, the major stream feeding the lake. Its waters, known to be nutrient-rich through contributions from sewage treatment plants and agricultural drainage, have been placed in Class 1.

In this study, Lake Tichigan has been defined to include the lake proper and what is commonly referred to as the "widening" in the Fox River. The lake proper has been assigned to Class 5 and the "widening" to several classes including 1, 2, and 4. Ground truth measurements indicate that the "widening" has a lower Secchi disc transparency and a substantially high chlorophyll a level.

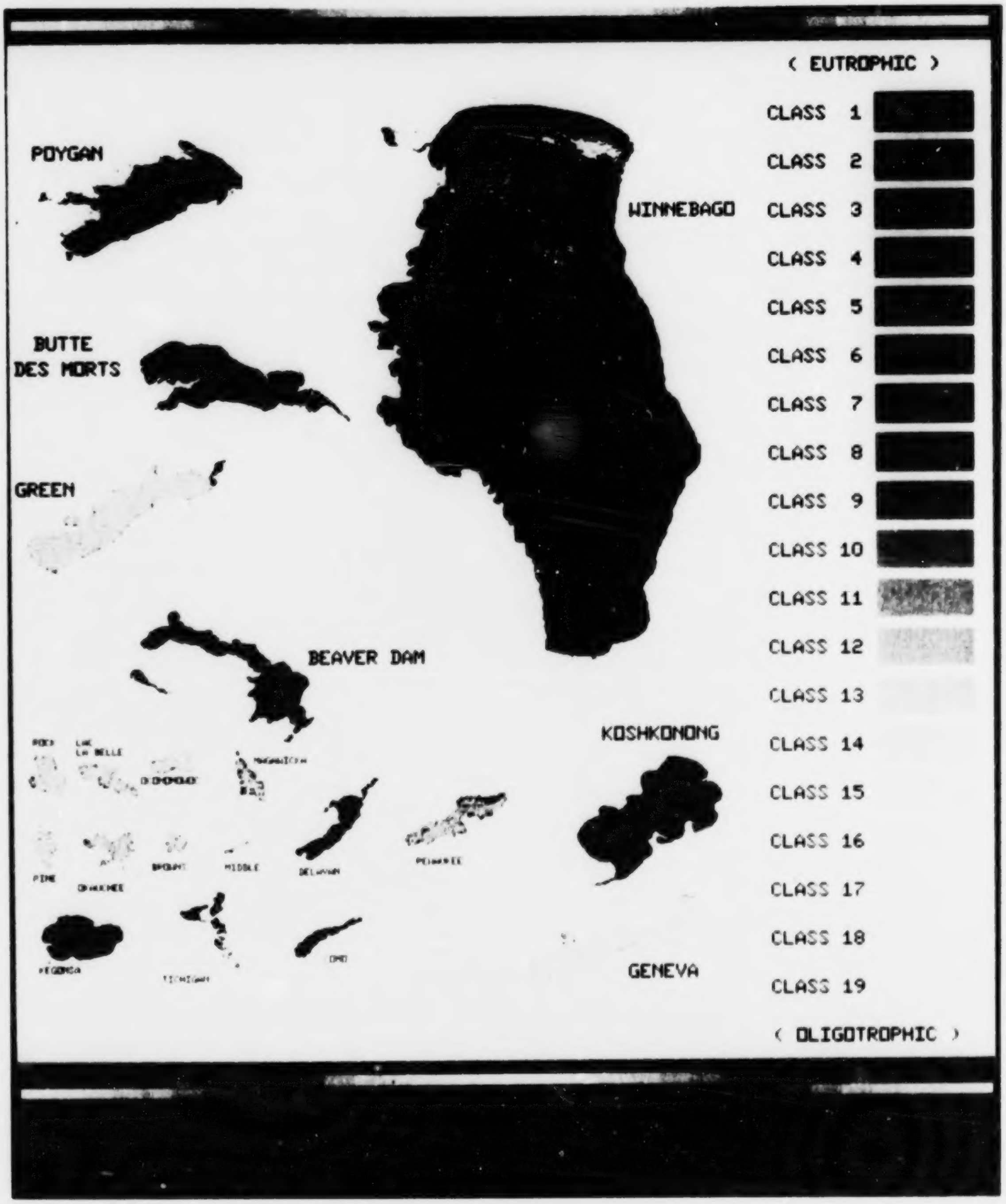

(EUTROPHIC)
CLASS 1
CLASS 2
CLASS 3
CLASS 4
CLASS 5
CLASS 6
CLASS 7
CLASS 8
CLASS 9
CLASS 10
CLASS 11
CLASS 12
CLASS 13
CLASS 14
CLASS 15
CLASS 16
CLASS 17
CLASS 18
CLASS 19
(OLIGOTROPHIC)
POYGAN
WINNEBAGO
BUTTE
DES MORTS
GREEN
BEAVER DAM
KOSHKONONG
GENEVA
LAC
LA BELLE
PINE
OKAUCHEE
MIDDLE
DELAVAN

Figure 37. ADP-classified lakes (9 August 1972), using 19 gray-levels, one for each class.

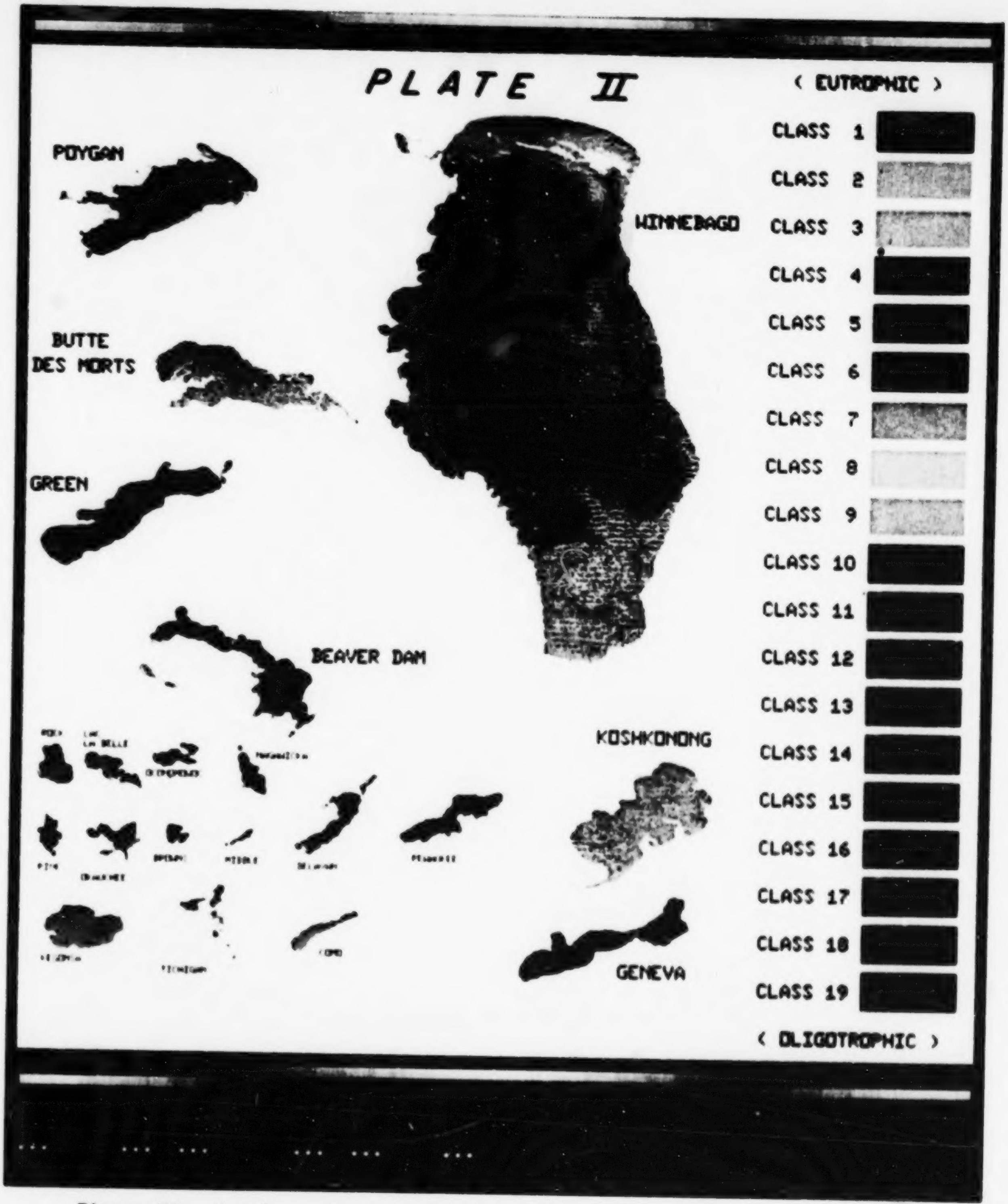


PLATE II
(EUTROPHIC)
POYGAN
WINNEBAGO
BUTTE DES MORTS
GREEN
BEAVER DAM
KOSHKONONG
GENEVA
CLASS 1
CLASS 2
CLASS 3
CLASS 4
CLASS 5
CLASS 6
CLASS 7
CLASS 8
CLASS 9
CLASS 10
CLASS 11
CLASS 12
CLASS 13
CLASS 14
CLASS 15
CLASS 16
CLASS 17
CLASS 18
CLASS 19
(OLIGOTROPHIC)

Figure 38. A color-enhanced version of the 19-class classification of the 20 lakes (9 August 1972).

The Class 1 water found along the northern shore of Lake Pewaukee may be related to the presence of algae and rooted emergent plants. The helicopter-borne survey teams reported algal scum covering the surface of the northern portion of the lake on 21 June 1972 and 19 August 1972. Heavy growths of emergents covered the lake shallows.

The appendix-like portion of Green Lake located at its northeast end is the area into which Silver Creek flows. The area receives a substantial nutrient load from a sewage treatment plant and the surrounding agricultural lands. Its pixels have been classified as belonging to Class 1 and Class 2.

White areas within the lake images are indicative of either clouds or land-related phenomena. The white area in the northeastern portion of Lake Winnebago represents cloud cover. The north-south linear feature located in the eastern end of Lake Butte des Morts is a causeway.

Complete accord does not exist between the trophic index values of the 20 lakes and the results of the ADP technique. The disparity is very evident in the cases of lakes Nagawicka, Koshkonong, and Oconomowoc where few, if any, pixels were found that fell into the class for which the lake served as a training area. Middle Lake contains pixels classified as belonging to Class 19, but they constitute only 15.4 percent of the total. This is not surprising because there is an indication in the three-dimensional color ratio model and the PC1 regression model for 9 August 1972 that a disparity exists between some of the lake PC1 values and their MSS data. The use of a smaller number of classes may very well yield more consistent results. This is an area in need of additional study.

The color-enhanced imagery, produced through an ADP technique, should prove to be of value, not only in comparing lakes with each other, but also for supplying information which can be used in the selection of future lake sampling sites. Further refinement should make the imagery a valued tool in lake survey and monitoring activities.

SECTION VIII

GENERAL SUMMARY

This research has focused on relationships between Earth Resources Technology Satellite-One (LANDSAT-1) multispectral scanner (MSS) data and the trophic status of selected lakes in Minnesota, Wisconsin, Michigan, and New York sampled by the U.S. Environmental Protection Agency's National Eutrophication Survey. Analyses were directed toward lake classification on the basis of ground truth, and the prediction of lacustrine trophic state indicator magnitudes and trophic state using MSS data.

Initially, 100 NES-sampled lakes were analyzed to ascertain their trophic status. Trophic indicators selected as parameters in the analyses included: chlorophyll a, conductivity, total phosphorus, total organic nitrogen, the inverse of Secchi disc transparency, and the yield of a standard algal assay procedure. Natural logarithm transformations were made on the data to produce a more-nearly normal distribution.

A complete linkage algorithm (McKeon, 1967) was used in conjunction with squared-Euclidian distance to examine the trophic status of the lake population for the presence of natural clusters or groups. The results are displayed in the form of a dendrogram (Figure 15).

The lake trophic indicator data were also subjected to a principal components analysis to reduce the dimensionality of the data from six-dimensional hyperspace to space of three or fewer dimensions. The eigenvectors and their associated eigenvalues were extracted from a p x p Pearson product-moment correlation matrix. The first principal component (normalized eigenvector) accounts for approximately 68 percent of the variation in the data. The second and third components represent about 14 percent and 8 percent of the variation, respectively. The results of the principal components analysis were used to ordinate the lakes in one-, two-, and three-dimensional space. The three-dimensional ordination is displayed as a "ball and wire" model (Figure 17).

A multivariate trophic state index was developed by evaluating the first principal component for each of the 100 NES-sampled lakes. The resultant values (PC1) are indicative of each lake's respective position on a multivariate trophic scale (the first principal axis). The larger the PC1 values, the closer the lake lies toward the eutrophic end of the scale. The coefficients of the first component are nearly equal in magnitude, suggesting that the first principal component represents a general measure of trophic state.

LANDSAT-1 MSS data, collected on 12 different dates from Minnesota, Wisconsin, and New York, were extracted from computer-compatible magnetic digital tapes (CCT's) using VICAR, a sophisticated software system at the Image Processing Laboratory (IPL), a support facility of the Jet Propulsion Laboratory (JPL). Each lake image was extracted from its terrain matrix through the use of a binary mask technique which employs a digital number (DN) level of 28 (8-bits of precision; 256 DN levels) as the water-land cutoff point. Descriptive statistics were computed for each lake including total number of pixels, mean DN values, standard deviations, and histograms. This was accomplished for each of the four MSS bands (GRN, RED, IR1, and IR2). A photographic concatenation was produced of the lakes extracted from each frame.

Regression models were developed to predict the magnitude of two trophic state indicators (Secchi disc transparency and chlorophyll a) using MSS data from two dates, 9 August 1972 (Wisconsin) and 14 August 1972 (Minnesota). A regression model was developed for each date of LANDSAT-1 MSS coverage using the multivariate trophic state index (PC1) as the dependent variable and the MSS color ratios as independent variables. Most of the modelling effort was directed toward NES-sampled lakes in eastern-southeastern Wisconsin. The Wisconsin area was selected because good LANDSAT-1 MSS coverage was available for a group of 20 lakes on three different dates.

A more flexible approach toward the study of PC1-MSS relationships was undertaken using three-dimensional MSS color ratio models. The MSS ratios GRNIR1, GRNRED, and REDIR1 were used to develop the three-dimensional "ball and wire" models. A model was constructed for each date of MSS coverage. In addition, a model was created for the Wisconsin lakes using mean color ratio values for the three sampling dates (9 August 1972, 11 June 1973, and 17 July 1973; Figure 36).

Automatic data processing (ADP) techniques were used in conjunction with the PC1 values for 20 Wisconsin lakes and MSS data 9 August 1972) to classify the lakes. A computer was programmed to recognize 19 trophic classes using the MSS color information contained in the 20 lakes. The classification was accomplished on a pixel-by-pixel basis using the MSS GRN, RED, and IR1 data. Output is in the form of statistical data and photographic products including 19-step gray scale prints (Figure 37) and 19-class color-enhanced photographs (Figure 38).

LAKE CLASSIFICATION USING GROUND TRUTH

The examination and classification of large numbers of lakes within realistic periods of time necessitates the use of automatic data processing techniques which incorporate classificatory methods, such as cluster analysis and principal components ordination.

The complete linkage algorithm used in this research did not produce three well-isolated clusters (groups) that can be readily associated with the traditional trophic classes of lakes - oligotrophic, mesotrophic, and eutrophic. This apparent failure is due in part to the lakes used in the study. Although the 100 lakes were selected to cover the range of lakes sampled during 1972 by the National Eutrophication Survey, the NES-sampled lake population is heavily weighted toward lakes with relatively poor water quality. The three-dimensional principal component ordination does not contain large well-defined clusters. The ordination results support the findings of the cluster analysis.

It is likely that there are no sharp discontinuities which clearly separate the members of a large population of lakes into the three commonly-referred-to trophic classes. Lakes of such a population may be characterized as constituting a hyper-dimensional cloud possessing a low degree of organization.

Cluster analysis techniques are a "heavy handed" approach to the lake classification problem because they will lead to clusters even if the data are random. The principal component analysis ordination does not presume the existence of clusters. The two methods are complementary and should be used in conjunction with one another.

The concept of a multivariate trophic state index, as defined by the position of a lake on the first principal component axis, merits further consideration. However, it must be kept in mind that a less sophisticated method, the mean composite rank (MCR) index, yielded similar results as measured by lake rank. The MCR system has the advantages of conceptual simplicity and ease of computation.

MSS Estimation of Lake Area and Selected Trophic State Indicators

The LANDSAT-1 MSS is an effective tool for the determination of the number and the areal extent of lakes. The use of a DN level of 28 (8-bits of precision) as the water-land cutoff point for the generation of the binary mask in conjunction with a pixel conversion factor of 0.48 (1 pixel = 0.48 hectares) gives lake area estimates generally within 10 percent of values derived from topographic sheets.

While the use of near-concurrent ground truth precludes more precise estimates, it has been demonstrated that good predictions of Secchi disc transparency can be achieved through the incorporation of MSS color ratios into regression models.

A measure of the chlorophyll a level can be obtained by using MSS color ratios as independent variables in regression models. However, caution must be used in the interpretation of the chlorophyll model predictions. The predicted values should be treated as a crude index rather than accurate estimations of chlorophyll a.

Models for the prediction of Secchi disc transparency and chlorophyll a are unique to the date of LANDSAT-1 MSS coverage. The models do not give good predictions when used with MSS data collected on different dates. Ground truth must be collected concurrently or near-concurrently with MSS coverage, and then the appropriate models must be constructed.

Although the need for ground truth places a restriction on the use of MSS data for the prediction of trophic state indicators, it still has utility in regions where lake concentrations result in the inclusion of hundreds and even thousands of lakes within a single MSS frame. Under such circumstances the collection of ground truth from a small number of "bench mark" lakes for the development of regression models would pay handsome dividends.

MSS Prediction of Lacustrine Trophic State

The MSS data can be used to give fair to very good estimates of lacustrine trophic state as defined by lake position on the first principal component axis. The regression models, developed using MSS color ratios as independent variables, are unique to the date of LANDSAT-1 coverage. Predictions made employing a specific model in conjunction with MSS data from other dates were statistically insignificant. Models developed from MSS data collected early in the open-water season are inadequate; better models were constructed using MSS data collected later in the season when the contrasts between lakes at different points on the trophic scale tend to be maximized.

Extraction Techniques and Products

While it is possible to extract MSS data related to lake trophic state and trophic indicators from EROS-supplied imagery, efforts to use this imagery are seriously impeded because the photographic products lack the requisite radiometric fidelity, a consequence of the scale compression induced by condensing the MSS intensity resolution from 127 levels (7-bit precision) to 16 gray levels. Data extracted from computer-compatible tapes (CCT's) must be used if the maximum benefits are to be derived from the LANDSAT-1 MSS. This is particularly important in water quality-related studies because the full range of water quality differences is contained in a relatively small number of DN levels. The computer-compatible tape approach to the problem of MSS data extraction has the added advantage of eliminating the errors introduced by differences in photographic products and the microdensitometer. CCT data extraction and processing techniques, which produce both MSS data statistics and photographic products, greatly increase the utility of the multispectral scanner.

Photographic products permit the rapid visual assessment of lake coverage by providing greater spatial resolution and a fraction of the bulk characteristic of line printer copy. It has been demonstrated that automatic digital processing techniques can produce trophic classifications which, when displayed as photographic imagery, can be incorporated into studies of lake water quality, water circulation patterns, and supply information for the selection of lake water sampling sites. The advantages of using CCT-produced photographs are particularly evident when the products are in the form of color-enhanced prints and transparencies.

LANDSAT-1 Coverage and Quality

Although LANDSAT-1 gives 18-day repetitive coverage, good frames were available for only a few days in the study area encompassing Minnesota, Wisconsin, Michigan, and New York. On many occasions, excessive cloud cover (greater than 10 percent) was present or one or more of the MSS bands was rated as poor or missing. Good coverage was virtually nonexistent for NES-sampled lakes in Michigan during 1972.

While it is recognized that the number of days with excessive cloud cover is a function of a region's weather and climate, and therefore its geographic location, - some regions (southwestern U.S.) have viewing conditions which are consistently better than other regions (northeastern U.S.) - it is apparent that good LANDSAT-1 MSS coverage is available on a very erratic basis, making systematic time-series studies difficult if not impossible in the study area and, indeed, for much of the eastern United States.

Information relating to water quality is found in each of the four MSS bands (GRN, RED, IR1, and IR2). However, the DN levels sensed for water bodies are few in number and are located at the lower end of the intensity scale. Surface water resource investigations would derive substantial benefits if the instrument gain were to be increased on the MSS. It is possible to switch to high gain in the GRN and RED bands.

SECTION IX

REFERENCES

1. Anderberg, M. R. 1973. Cluster analysis for applications. New York: Academic Press. 373 pp.

2. Anderson, T. W. 1958. An introduction to multivariate statistical analysis. New York: John Wiley and Sons. 374 pp.

3. Anderson, R. R. and F. J. Wobber. 1973. Wetlands mapping in New Jersey. Photogrammetric Engineering. 39(4):353-358.

4. Anonymous. 1973. IPL user documentation for applications programs. Revision 9. Pasadena: Jet Propulsion Laboratory, California Institute of Technology. 206 pp.

5. Arvensen, J. C., E. C. Weaver and J. P. Millard. 1971. Rapid assessment of water pollution by airborne measurement of chlorophyll. Proceedings Joint Conference on Sensing of Environmental Pollutants. American Institute of Aeronautics and Astronautics. Palo Alto. AIAA-71-1097. 7 pp.

6. Atkins, W. R. G. and H. H. Poole. 1952. An experimental study of the scattering of light by natural waters. Proceedings of the Royal Society (London). Series B. 140:321-338.

7. Atwell, B. H. and G. C. Thomann. 1972. Mississippi Sound remote sensing study. Fourth Annual Earth Resources Program Review. January 17-21, 1972. NASA Manned Spacecraft Center, Houston. 3(13):1-17.

8. Barr, B. G. 1973. Detection of water bodies in Saline County, Kansas. NASA-CR-132191. NTIS-E73-10684. 10 May 1973. 4 pp.

9. Beeton, A. M. 1965. Eutrophication of the St. Lawrence Great Lakes. Limnology and Oceanography. 10(2):240-254.

10. Beeton, A. M. and W. T. Edmondson. 1972. The eutrophication problem. Journal Fisheries Research Board of Canada. 29(6):673-682.

11. Berg, C. O. 1963. Middle Atlantic States. In: Limnology in North American. Edited by D. G. Frey. Madison: University of Wisconsin Press. pp. 191-237.

12. Billingsley, F. C. and A. F. H. Goetz. 1973. Computer techniques used for some enhancements of ERTS images. In: Symposium on Significant Results obtained from the Earth Resources Technology Satellite-1. 5-9 March 1973. NASA (Goddard Space Flight Center). Edited by S. C. Freden, E. P. Mercanti, and M. A. Becker. I(Technical Presentations, Section B):1159-1167.

13. Birge, E. A. and C. Juday. 1929. Transmission of solar radiation by the waters of inland lakes. Transactions Wisconsin Academy Science Arts Letters. 24:509-580.

14. ______________. 1930. A second report on solar radiation and inland lakes. Transactions Wisconsin Academy Science Arts Letters. 25:285-335.

15. ______________. 1931. A third report on solar radiation and inland lakes. Transactions Wisconsin Academy Science Arts Letters. 26:383-425.

16. ______________. 1932. Solar radiation and inland lakes, fourth report. Transactions Wisconsin Academy Science Arts Letters. 27:523-562.

17. Black, A. P. and R. F. Christman. 1963. Characteristics of colored surface water. Journal American Water Works Association. 55(6):753-770.

18. Blackwell, R. J. and F. C. Billingsley. 1973. JPL/IPL multispectral photography methods for the detection of algae. Report 730-00048-0-8240. Pasadena: Jet Propulsion Laboratory, California Institute of Technology. 15 pp.

19. Blackwell, R. F. and D. H. Boland. 1974. Computer analysis of lakes from ERTS imagery. In: Northwest '74 Pacific Regional Symposium on Computing the Resources Industry. Canadian Information Processing Society. 23-24 May 1974. Vancouver, B. C. pp. 147-157.

20. Boland, D. H. P. 1975. An evaluation of the Earth Resources Technology Satellite (ERTS-1) multispectral scanner as a tool for the determination of lacustrine trophic state. Ph. D. Thesis. Oregon State University: Corvallis. 311 pp.

21. Boland, D. H. P. and R. J. Blackwell. 1975. The LANDSAT-1 multispectral scanner as a tool in the classification of inland lakes. In: Proceedings NASA Earth Resources Survey Symposium. 9-12 June 1975. Houston, Texas. I-A (Technical Session). NASA TM X-58168. JSC-09930. pp. 419-442.

22. Bowker, D. E., P. Fleischer, T. A. Gosink, W. J. Hanna, and J. Ludwick. 1973. Correlation of ERTS multispectral imagery with suspended matter and chlorophyll in Lower Chesapeake Bay. In: Symposium on Significant Results obtained from the Earth Resources Technology Satellite-1. 5-9 March 1973. NASA (Goddard Space Flight Center). I(Section B):1291-1297.

23. Bressette, W. E. and D. E. Lear, Jr. 1973. The use of near-infrared reflected sunlight for biodegradable pollution monitoring. In: Proceedings Second Conference on Environmental Research Center. Las Vegas, Nevada. Session I:70-89.

24. Brezonik, P. L. 1969. Eutrophication: the process and its modeling potential. In: Proceedings Workshop Modeling the Eutrophication Process. Gainesville: University of Florida. pp. 68-110.

25. Brezonik, P. L. and E. E. Shannon. 1971. Trophic state of lakes in north central Florida. Publication 13. Florida Water Resources Research Center. Gainesville: University of Florida. 102 pp.

26. Brown. W. L., F. C. Polcyn, J. R. McKimmy, and O. E. Prewett. 1972. Calculating water quality parameters using remotely sensed scanner data. In: Proceedings of the Eighth International Symposium on Remote Sensing of Environment. 2-6 October 1972. Ann Arbor: University of Michigan. 1:563-567.

27. Carlson, P. R. 1973. Principal sources and dispersal patterns of suspended particulate matter in nearshore surface waters of the northeast Pacific Ocean and the Hawaiian Islands. Progress Report 1 April - 31 May 1973. NASA-CR-133155. NTIS-#73-10788. 12 June 1973. 9 pp.

28. Chase, P. E. and V. E. Smith. 1973. Utilization of ERTS-1 data to monitor and classify eutrophication of inland lakes. Interim Report September 1972 - January 1973. NASA-CR-130555. NTIS-E73-10299. 70 pp.

29. Chase, P., E. L. Reed, and V. E. Smith. 1973. Utilization of ERTS-1 data to monitor and classify eutrophication of inland lakes. In: Symposium of Significant Results obtained from the Earth Resources Technology Satellite-1. 5-9 March 1973. NASA (Goddard Space Flight Center). I(Section B):1597-1604.

30. Clapp, J. L. 1972. Application of remote sensing to water resources problems. In: Fourth Annual Earth Resources Program Review. 17-21 January 1972. NASA Manned Spacecraft Center, Houston. 2(46):1-39.

31. Clarke, G. L. 1969. The significance of spectral changes in light scattered by the sea. In: Remote Sensing in Ecology. Edited by P. L. Johnson. Athens: University of Georgia Press. pp. 164-172.

32. Clarke, G. L. and H. R. James. 1939. Laboratory analysis of the selective absorption of light by sea water. Journal Optical Society America. 29:43-55.

33. Clarke, G. L., G. C. Ewing, and C. J. Lorenzen. 1969. Remote measurement of ocean color as an index of biological productivity. A preliminary summary report. In: Proceedings of the Sixth International Symposium on Remote Sensing of Environment. 13-16 October 1969. Ann Arbor: University of Michigan. pp. 991-1001.

34. _____________. 1970. Spectra of backscattered light from the sea obtained from aircraft as a measure of chlorophyll concentration. Science. 167:1119-1121.

35. Coker, A. E., A. Higer, and C. R. Goodwin. 1973. Detection of turbidity dynamics in Tampa Bay, Florida using multispectral imagery from ERTS-1. In: Symposium on Significant Results obtained from the Earth Resources Technology Satellite-1. 5-9 March 1973. NASA (Goddard Space Flight Center). I(Section B):1715-1726.

36. Collins, J. R. 1925. Change in the infrared absorption spectrum of water with temperature. Physics Review. 26:771.

37. Colwell, R. N. 1973. Remote sensing as an aid to the management of earth resources. American Scientist. 61(2):175-183.

38. Committee on Colorimetry. 1966. The science of color. Sixth Edition. Washington, D. C.: Optical Society of America. 385 pp.

39. Conrod, A. C. and K. A Rottweiler. 1971. Water quality measurements with airborne multispectral scanners. Paper 71-1096 presented at Joint Conference on Sensing of Environmental Pollutants. American Institute of Aeronautics and Astronautics. 8-10 November 1971. Palo Alto, California. 8 pp.

40. Crew, G. W. 1973. Remote detection of water pollution with MOCS: an imaging multispectral scanner. In: Proceedings Second Conference on Environmental Quality Sensors. 10-11 October 1973. National Environmental Research Center. Las Vegas, Nevada. Session II:17-39.

41. Curran, R. J. 1972. Ocean color determination through a scattering atmosphere. Applied Optics. 11(8):1857-1866.

42. Davis, F. J. 1941. Surface loss of solar and sky radiation by inland lakes. Transactions Wisconsin Academy Science Arts Letters. 33:83-93.

43. Davis, W. M. 1882. On the classification of lake basins. Proceedings Boston Society Natural History. 21:315-381.

44. ______________. 1887. The classification of lakes. Science. 10(241):142-143.

45. Dawson, L. H. and E. O. Hulburt. 1937. The scattering of light by water. Journal Optical Society America. 27:199-201.

46. Deevey, E. S. 1942. Some geographic aspects of limnology. The Science Monthly. 55:423-434.

47. Detwyler, T. R. 1971. Modern man and environment. In: Man's Impact on Environment. Edited by T. R. Detwyler. New York: McGraw-Hill. 731 pp.

48. Donaldson, J. R. 1969. The classification of lakes. In: Proceedings of the Eutrophication-Biostimulation Assessment Workshop. 19-21 June 1969. Held at Hotel Claremont, Berkeley, California. Sponsored by University of California (Berkeley) and Pacific Northwest Water Laboratory, U. S. Environmental Protection Agency. pp. 171-185.

49. Draper, N. R. and H. Smith. 1966. Applied regression analysis. New York: John Wiley and Sons. 407 pp.

50. Duntley, S. Q. 1963. Light in the sea. Journal Optical Society America. 53:214-233.

51. Dybdahl, A. W. 1973. Detection of dissolved oxygen in water through remote sensing techniques. Progress Report. In: Proceedings Second Conference on Environmental Quality Sensors. 10-11 October 1973. National Environmental Research Center. Las Vegas, Nevada. Section VIII:48-66.

52. Edmondson, W. T. 1974. Review of: Environmental phosphorus handbook, Edited by E. J. Griffith, A. Beeton, J. M. Spencer, and D. T. Mitchell. New York: Wiley-Interscience. 1973. 718 pp. In: Limnology and Oceanography. 19(2):369-375.

53. Erb, R. B. 1973. Utilization of ERTS-1 data in the Houston area. NASA-TM-X-69261. NTIS-E73-10672. 12 March 1973. 2 pp.

54. Ewan, T. 1894. On the absorption spectra of dilute solutions. Proceedings Royal Society (London). 57:117-161.

55. Forel, F. A. 1889. Ricerche fisiche sui laghi d'Insubria. Reale Istituto Lombardo di Scienze e Lettere. Rendiconti, Milano. Second Series. 22:739-742.

56. Fortunatov, M. V. 1957. Aerial methods and their application in limnological study in inland water bodies. In: Transactions of the Sixth Conference on the Biology of Inland Waters. Edited by E. N. Pavlovskii. Original in Russian. Israel Program for Scientific Translation. Jerusalem: LPST Press. 1969. pp. 591-601.

57. Fraser, A. R. and M. Kovats. 1966. Stereoscopic models of multivariate statistical data. Biometrics. 22(2):358-367.

58. Freden, S. C. 1973. Introduction: performance of sensors and systems. In: Earth Resources Technology Satellite-1 Symposium Proceedings. 29 September 1972. NASA (Goddard Space Flight Center). Compiled by W. A. Finch, Jr. pp. 1-6.

59. Frieden, H. 1971. Image processing system VICAR guide to system use. Original 1 October 1968. Revised July 1971. Jet Propulsion Laboratory. California Institute of Technology. Pasadena. RO 71-135. 44 pp.

60. Fruh, E. G., K. M. Stewart, G. F. Lee, and G. A. Rohlich. 1966. Measurements of eutrophication and trends. Water Pollution Control Federation Journal. 38(8):1237-1258.

61. Gerd, W. V. 1957. An attempt at the biolimnological regionalization of the USSR. In: Transactions of the Sixth Conference on the Biology of Inland Waters. Edited by E. N. Pavlovskii. Original in Russian. Israel Program for Scientific Translations. Jerusalem: IPST Press. 1969. pp. 138-145.

62. Gower, J. C. 1966. Some distance properties of latent root and vector methods used in multivariate analysis. Biometrika. 53:325-338.

63. Gower, J. C. 1967. A comparison of some methods of cluster analysis. Biometrics. 23(4):623-637.

64. Gramms, L. C. and W. C. Boyle. 1971. A literature review of remote sensing for water quality. Remote Sensing Program Report Number 7. Madison: University of Wisconsin. 34 pp.

65. Guthrie, D., C. Avery, and K Avery. 1973. Statistical interactive programming system (*SIPS) user's reference manual. Technical Report Number 36. Department of Statistics. Corvallis: Oregon State University. 111 pp.

66. Hammond, E. H. 1964. Analysis of properties in land form geography: An application to broad-scale landform mapping. Annals American Association Geographers. 54:11-23.

67. Hansen, K. 1962. The dystrophic lake type. Hydrobiologia. 19(2):183-191.

68. Harding, S. T. 1942. Lakes. pp. 220-243. In: Hydrology. Edited by O. E. Meinzer. New York: McGraw-Hill. Dover edition by Dover Publications: New York. 712 pp.

69. Hasler, A. D. 1947. Eutrophication of lakes by domestic drainage. Ecology. 28:383-395.

70. Hasler, A. D. and B. Ingersoll. 1968. Dwindling lakes. Natural History. 77(9):8-19.

71. Hazen, A. 1892. A new color standard for natural waters. American Chemical Society Journal. 14:300-310.

72. Hidalgo, J. U., A. E. Smalley, K. H. Faller, and M. B. Irvin. 1973. Preliminary study of Lake Pontchartrain and vicinity using remotely sensed data from the ERTS-A satellite. Progress Report. NASA-CR-132010. NTIS-E73-10613. 15 May 1973. 6 pp.

73. Hoffer, R. M., P. E. Anuta, and T. L. Phillips. 1972. ADP, multiband, and multiemulsion digitized photos. Photogrammetric Engineering. 38(10):989-1001.

74. Hom, L. W. 1968. Remote sensing of water pollution. Journal Water Pollution Control Federation. 40:1728.

75. Holmes, R. W. 1970. The Secchi disk in turbid coastal waters. Limnology and Oceanography. 15(5):688-694.

76. Hooper, F. F. 1969. Eutrophication indices and their relation to other indices of ecosystem change. In: Eutrophication: Causes, Consequences, Correctives. Proceedings of a Symposium. 11-15 June 1967. University of Wisconsin. Washington, D. C.: National Academy of Science. pp. 225-235.

77. Horan, J. J., D. S. Schwartz, and J. D. Love. 1974. Partial performance degradation of a remote sensor in a space environment, and some probable causes. Applied Optics. 13(5):1230-1237.

78. Hotelling, H. 1933a. Analysis of a complex of statistical variables into principal components (I. Introduction). The Journal of Educational Psychology. 24:417-441.

79. ______________. 1933b. Analysis of a complex of statistical variables into principal components (II). The Journal of Educational Psychology. 24:498-520.

80. ______________. 1936. Simplified calculation of principal components. Psychometrika. 1(1):27-35.

81. Hulburt, E. O. 1945. Optics of distilled and natural water. Journal of the Optical Society of America. 35(11):698-705.

82. Hunt, C. B. 1967. Physiography of the United States. San Francisco: W. H. Freeman. 480 pp.

83. Hulstrom, R. L. 1973. The cloud bright spot. Photogrammetric Engineering. 39(4):370-376.

84. Hutchinson, G. E. 1957. A treatise on limnology. Volume I. Geography, physics, and chemistry. New York: John Wiley. 1015 pp.

85. ______________. 1967. A treatise on limnology. Volume II. Introduction to lake biology and the limnoplankton. New York: John Wiley. 1115 pp.

86. ______________. 1973. Eutrophication. The scientific background of a contemporary practical problem. American Scientist. 61:269-279.

87. James, H. R. and E. A. Birge. 1938. A laboratory study of the absorption of light by lake waters. Transactions Wisconsin Academy Science Arts Letters. 31:1-154.

88. James, H. R. 1941. Beer's law and the properties of organic matter in lake waters. Transactions Wisconsin Academy Science Arts Letters. 33:73-82.

89. Järnefelt, H. 1958. On the typology of northern lakes. In: Proceedings International Association Theoretical Applied Limnology (International Vereinigung für Theoretische und Angewandte Limnologie). Volume XIII. Congress in Finland 1956. Edited by T. T. Macan. Stuttgart: 1958. pp. 228-235.

90. Jerlov, N. G. 1968. Optical oceanography. Elsevier Oceanography Series. Volume 5. Amsterdam: Elsevier. 194 pp.

91. Johnson, S. C. 1967. Hierarchical clustering schemes. Psychometrika. 32(3):241-254.

92. Juday, C. and E. A. Birge. 1933. The transparency, the color, and the specific conductance of the lake water of northeastern Wisconsin. Transaction Wisconsin Academy Science Arts Letters. 28:205-259.

93. Katzoff, S. 1962. The electromagnetic-radiation environment of a satellite, Part 1, range of thermal to X-radiation. NASA TN D-1360. N62-15249. 75 pp.

94. Kelly, M. G. and A. Conrod. 1969. Aerial photographic studies of shallow water benthic ecology. In: Remote Sensing in Ecology. Athens: University of Georgia Press. pp. 173-184.

95. Ketelle, M. J. and P. D. Uttormark. 1971. Problem lakes in the United States. Water Pollution Control Research Series. Report Number 16010 EHR. U. S. Environmental Protection Agency. 282 pp.

96. Kiefer, R. W. and J. P. Scherz. 1970. Applications of airborne remote sensing technology. Journal Surveying Mapping Division. Proceeding American Society Civil Engineers. SU1(7225):57-80.

97. _____________. 1971. Aerial photography for water resources studies. Journal Surveying Mapping Division. Proceedings American Society Civil Engineers. SU2(8545):321-333.

98. Klemas, V. 1973. Applicability of ERTS-1 imagery to the study of suspended sediment and aquatic fronts. In: Symposium on Significant Results obtained from the Earth Resources Technology Satellite-1. NASA (Goddard Space Flight Center). I(Section B):1725-1290.

99. Kolipinski, M. C. and A. L. Higer. 1968. Applications of aerial photography and remote sensing to hydrobiological research in south Florida. Open File Report. U. S. Geological Survey. Water Resources Division. Miami, Florida. 7 pp.

100. Kritikos, H., L. Yorinks, and H. Smith. 1973. Water Quality analysis using ERTS-A data. In: Proceedings Second Conference on Environmental Quality Sensors. 10-11 October 1973. National Environmental Research Center. Las Vegas, Nevada. p. VII:37-56.

101. Lance, G. N. and W. T. Williams. 1967a. A general theory of classificatory sorting strategies I. Hierarchic systems. The Computer Journal. 9:373-380.

102. ______________. 1967b. A general theory of classificatory sorting strategies II. Clustering systems. The Computer Journal. 10:271-277.

103. Larkin, P. A. and T. G. Northcote. 1958. Factors in lake typology in British Columbia, Canada. In: Proceedings International Association Theoretical Applied Limnology (Verh. Internat. Ver. Limnol.). 13:252-263.

104. Lind, A. O. 1973. Survey of lake flooding from ERTS-1: Lake Champlain. NASA-CR-133138. NTIS-#72-10771. June 1973. 11 pp.

105. Lind, A. O. and E. B. Henson. 1973. Pollution monitoring in Lake Champlain using ERTS-1 imagery. NASA-CR-133086. NTIS-E73-10742. June 1973. 8 pp.

106. Lindeman, R. L. 1942. The trophic-dynamic aspect of ecology. Ecology. 23(4):399-418.

107. Look, D. C., A. L. Crosbie, B. F. Armaly, and H. F. Nelson. 1973. Influence of absorption coefficient on reflectance of water. Journal Water Pollution Control Federation. 45:936-939.

108. Lorenzen, C. J. 1970. Survey chlorophyll as an index of the depth, chlorophyll content, and primary productivity of the euphotic layer. Limnology and Oceanography. 15(3):479-480.

109. Lueschow, L. A., J. M. Helm, D. R. Winter, and G. W. Karl. 1970. Trophic nature of selected Wisconsin lakes. Wisconsin Academy Sciences Arts Letters. 58:237-264.

110. McKeon, J. J. 1967. Hierarchical cluster analysis computer program. Biometrics Laboratory. George Washington University, Kensington, Maryland. 6 pp.

111. Margalef, R. 1958. "Trophic" typology versus biotic typology as exemplified in the regional limnology of northern Spain. In: Proceedings International Association Theoretical Applied Limnology. 13:339-349.

112. Maugh, T. H. 1973. ERTS: Surveying earth's resources from space. Science. 180(4081):49-1044.

113. ______________. 1973. ERTS (II): A new way of viewing the earth. Science. 180(4082):171-173.

114. Morrison, D. F. 1967. Multivariate statistical methods. New York: McGraw-Hill. 338 pp.

115. Moss, W. W. 1967. Some new analytic and graphic approaches to numerical taxonomy, with an example for the Dermanyssidae (Acari). Systematic Zoology. 16:177-207.

116. ______________. 1968. Experiments with various techniques of numerical taxonomy. Systematic Zoology. 20:309-330.

117. Moyle, J. B. 1945. Classification of lake waters upon the basis of hardness. Proceedings Minnesota Academy Science. 13:8-12.

118. ______________. 1946. Some indices of lake productivity. Transactions of the American Fisheries Society. 76:322-334.

119. Minnesota Department of Conservation. 1968. Inventory of Minnesota lakes. Bulletin Number 25. Division Water, Soils, and Minerals. 498 pp.

120. Mueller, J. L. 1972. Remote measurement of chlorophyll concentration and Secchi-depth using the principal components of the ocean's color spectrum. In: Fourth Annual Earth Resources Program Review. 17-21 January 1972. NASA Manned Spacecraft Center, Houston. 4(105):1-13.

121. Nace, R. L. 1960. Water management, agriculture, and groundwater supplies. U. S. Geological Survey Circular 415. 11 pp.

122. National Aeronautics and Space Administration. 1972a. NASA earth resources technology satellite data users handbook. Goddard Space Flight Center. Document Number 71SD4249. Subject to revision.

123. National Aeronautics and Space Administration. 1972b. ERTS investigators' bulletin. A(4). 8 August 1972. 1 pp.

124. Naumann, E. 1919. Nagra synpunkte angaende planktons ökologi. Med. sarskild hänsyn till fytoplanton. Svensk Botanisk Tidskrift. 13:129-158.

125. _____________. 1931. Limnologische terminologie. Urban and Schwarzenberg, Berline-Wien. (pp. 153 and 413). 776 pp.

126. National Eutrophication Survey. 1974. National Eutrophication Survey methods for lakes sampled in 1972. U. S. Environmental Protection Agency National Eutrophication Survey Working Paper Number 1. PNERL (NERC-Corvallis) and NERC-Las Vegas. 40 pp.

127. Nielsen, U. 1972. Agfacontour film for interpretation. Photogrammetric Engineering. 38(1):1009-1104.

128. Nordberg, W. 1972. Written communication dated 9 November 1972. NASA Goddard Space Flight Center. Greenbelt, Maryland. 3 pp.

129. Padron, M. 1969. An axiomatic basis and computational methods for optimal clustering. Technical Report 18. Department of Industrial and Systems Engineering. University of Florida: Gainesville. 171 pp.

130. Pearsall, W. H. 1932. Phytoplankton in the English lakes. II. The composition of the phytoplankton in relation to dissolved substances. Journal of Ecology. 20(2):241-262.

131. Pennak, R. W. 1958. Regional lake typology in northern Colorado, U. S. A. In: Proceedings International Association Theoretical Applied Limnology. 13:262-283.

132. Piech, K. R. and J. E. Walker. 1971. Aerial color analyses of water quality. Journal Survey Mapping Division. Proceedings American Society Civil Engineers. SU2(8507):185-197.

133. Pietenpol, W. B. 1918. Selective absorption in the visible spectrum of Wisconsin waters. Transactions Wisconsin Academy Science Arts Letters. 19:562.

134. Pluhowski, E. J. 1973. Remote sensing of turbidity plumes in Lake Ontario. In: Symposium on Significant Results obtained from the Earth Resources Technology Satellite-1. NASA (Goddard Space Flight Center). 5-9 March 1973. I(Section B):837-846.

135. Polcyn, F. C. and D. R. Lynzenga. 1973. Calculations of water depth from ERTS-MSS data. In: Symposium on Significant Results obtained from the Earth Resources Technology Satellite-1. 5-9 March 1973. NASA (Goddard Space Flight Center). I(Section B):1433-1441.

136. Raman, C. V. 1922. On the molecular scattering of light in water and the colour of the sea. Proceedings Royal Society (London). Ser. A. 101:64-79.

137. Ranz, E. and S. Schneider. 1970. Der Aquidensitenfilm als Hilfsmittel bei der Photointerpretation. Bildmessung und Luftbildwesen. 2:123-134.

138. Rawson, D. S. 1956. Algal indicators of trophic lake types. Limnology and Oceanography. 1(1):18-25.

139. _____________. 1960. A limnological comparison of twelve large lakes in northern Saskatchewan. Limnology and Oceanography. 5(2):195-211.

140. Reeves, C. C. 1973. Dynamics of playa lakes in the Texas high plains. Symposium on Significant Results Obtained from the Earth Resources Technology Satellite-1. 5-9 March 1973. NASA (Goddard Space Flight Center). I(Section B):809-817.

141. Robinove, C. J. 1965. Infrared photography and imagery in water resources research. Journal American Water Works Association. 57(7):834-840.

142. Rodhe, W. 1969. Crystallization of eutrophication concepts in northern Europe. In: Eutrophication: Causes, Consequences, Correctives. Proceedings of a Symposium. 11-15 June 1967. University of Wisconsin. Washington, D. C.: National Academy of Science. pp. 50-64.

143. Rogers, R. H. and K Peacock. 1973. A technique for correcting ERTS data for solar and atmospheric effects. In: Symposium on Significant Results obtained from the Earth Resources Technology Satellite-1. 5-9 March 1973. NASA (Goddard Space Flight Center). I(Section B):1115-1122.

144. Roger, R. H. and V. E. Smith. 1973. Utilization of ERTS-1 data to monitor and classify eutrophication of inland lakes. Interim Report for February 1973-July 1973. NTIS-E73-10898. 117 pp.

145. Rohlf, F. J. 1968. Stereograms in numerical taxonomy. Systematic Zoology. 17:246-255.

146. Rohlf, F. J. 1968. Grafpac, Graphic output subroutines for the GE 635 computer. Computer Contribution Number 36. Edited by D. F. Merriam. State Geological Survey. University of Kansas: Lawrence. 50 pp.

147. Ross, D. S. 1973a. Water depth estimation with ERTS-1 imagery. In: Symposium on Significant Results obtained from the Earth Resources Technology Satellite-1. 5-9 March 1973. NASA (Goddard Space Flight Center). I(Section B):1423-1432.

148. ______________. 1973b. Atmospheric effects in multispectral photographs. Photogrammetric Engineering. 39(4):377-384.

149. Rossolimo, L. L. 1971. Anthropogenic eutrophication of lakes and reservoirs: nature of the problem and research goals. Hydrobiological Journal. 7(3):90-97.

150. Round, F. E. 1958. Algal aspects of lake typology. In: Proceedings International Association Theoretical Applied Limnology. 13:306-310.

151. Russell, I. C. 1895. Lake of North America. A reading lesson for students of geography and geology. Boston: Gin and Company. 125 pp.

152. Ruttner, F. 1963. Fundamentals of limnology. Third edition. Translated by D. G. Frey and F. E. J. Fry. Toronto: University of Toronto Press. 295 pp.

153. Sawyer, C. N. 1946. Fertilization of lakes by agricultural and urban drainage. Journal New England Water Works Association. 61:109-127.

154. Sawyer, W. R. 1931. The spectral absorption of light by pure water and Bay of Fundy water. Contribution to Canadian Biology and Fisheries being Studied from the Biological Stations of Canada. Series D. Hydrographic. 7(8):73-89.

155. Scherz, J. P., D. R. Graff, and W. C. Boyle. 1969. Photographic characteristics of water pollution. Photogrammetric Engineering. 35:38-43.

156. Scherz, J. P. 1971a. Monitoring water pollution by means of remote sensing techniques. Remote Sensing Program Report Number 3. Madison: University of Wisconsin. 27 pp.

157. ______________. 1971b. Monitoring water pollution by remote sensing. Journal Surveying Mapping Division. Proceedings American Society Civil Engineers. 97:307-320.

158. Schmer, F. A., M. J. Tipton, D. W. Ryland, J. Hayden, and G. Beaver. 1972. Investigation of lake water quality in eastern South Dakota. In: Proceedings Eighth International Symposium Remote Sensing Environment. 2-6 October 1972. Ann Arbor: University of Michigan. 1:553-562.

159. Schnell, G. D. 1970a. A phenetic study of the suborder Lari (Aves)/I. Methods and results of principal components analyses. Systematic Zoology. 19:35-37.

160. ______________. 1970b. A phenetic study of the suborder Lari (Aves)/II. Phenograms, discussion, and conclusions. Systematic Zoology. 19:264-302.

161. Shannon, E. E. 1970. Eutrophication-trophic state relationships in north and central Florida lakes. Doctoral dissertation. Gainesville: University of Florida. 257 pp.

162. Shannon, E. E. and P. L. Brezonik. 1972a. Eutrophication analysis: a multivariate approach. Journal Sanitary Engineering Division. Proceedings American Society Civil Engineers. 98(SA1, 8735):35-37.

163. ______________. 1972b. Relationships between trophic state and nitrogen and phosphorus loading rates. Environmental Science and Technology. 6(8):719-725.

164. Seal, H. L. 1964. Multivariate statistical analysis for biologists. London: Methuen. 207 pp.

165. Seddon, B. 1972. Aquatic macrophytes as limnological indicators. Freshwater Biology. 2:107-130.

166. Sheldon, A. 1972. A quantitative approach to the classification of inland waters. In: Natural Environments. Studies in Theoretical and Applied Analysis. Edited by J. V. Krutilla. Baltimore: John Hopkins University Press. pp. 205-261.

167. Silvestro, F. B. 1970. Remote sensing analysis of water quality. Journal Water Pollution Control Federation. 40:553-561.

168. Smith, R. C., J. E. Tyler, and C. R. Goldman. 1973. Optical properties and color of Lake Tahoe and Crater Lake. Limnology and Oceanography. 18(2):189-199.

169. Sneath, P. H. A. and R. R. Sokal. 1973. Numerical taxonomy: The principles and practice of numerical classification. San Francisco: F. H. Freeman. 573 pp.

170. Snedecor, G. W. and W. G. Cochran. 1967. Statistical methods. Sixth edition. Ames: Iowa State University Press. 593 pp.

171. Soil Survey Staff. 1960. Soil Classification: A comprehensive system, 7th approximation. U. S. Department of Agriculture. Soil Conservation Service. 265 pp.

172. ______________. 1967. Supplement to soil classification system (7th approximation). U. S. Department of Agriculture. Soil Conservation Service. 207 pp.

173. Sokal, R. R. and F. J. Rohlf. 1962. The comparison of dendograms by objective methods. Taxon. 11(2):33-40.

174. Sokal, R. R. and P. H. A. Sneath. 1963. Principals of numerical taxonomy. San Francisco: W. H. Freeman. 359 pp.

175. Specht, M. R., D. Needler, and N. L. Fritz. 1973. New color film for water-photography penetration. Photogrammetric Engineering. 39(4):359-369.

176. Spiess, F. N. 1970. Oceanic environment. In: Hydronautics. Edited by: H. E. Sheets and V. T. Boatwright, Jr. New York: Academic Press.

177. Stewart, K. M. and G. A. Rohlich. 1967. Eutrophication -- A review. Publication Number 35. California State Water Quality Control Board. Sacramento. 188 pp.

178. Strahler, A. N. 1969. Physical geography. Third edition. New York: John Wiley. 733 pp.

179. Strong, A. E. 1973. ERTS-1 observes algal blooms in Lake Erie and Utah Lake. Symposium on Significant Results obtained from the Earth Resources Technology Satellite-1. 5-9 March 1973. NASA (Goddard Space Flight Center). I(Section B): 1605-1612.

180. Szekielda, K. H. and R. J. Curran. 1972. Chlorophyll structure in the ocean. NASA-72-31338. NTIS-E72-10047. 29 September 1972. 2 pp.

181. Thienemann, A. 1918. Untersuchungen uber die Beziechungen zwischen dem Sauerst offgehalt der Wassers und der Zusammensetzung der Fauna in norddeutchen Seen. Archiv Fuer Hydrobiologie. 12:1-65.

182. Thornthwaite, C. W. 1948. An approach toward a rational classification of climate. Geographical Review. 38:55-94.

183. Trewartha, G. T. 1968. An introduction to climate. New York: McGraw-Hill. 408 pp.

184. Tyler, J. E. 1968. The Secchi disc. Limnology and Oceanography. 13(1):1-6.

185. Ule, W. 1892. Die Bestimmung der Wasserfarbe in den Seen. A. Petermanns Mittheilungen aus Justus Perthes' Geographisher Anstalt. 38:70-71.

186. U. S. Environmental Protection Agency. 1971. Algal assay procedure bottle test. National Eutrophication Research Program. Pacific Northwest Water Laboratory. Corvallis. 82 pp.

187. U. S. Department of Agriculture. 1941. Climate and Man. Yearbook of Agriculture. Washington, D. C.: U. S. Government Printing Office. 1248 pp.

188. U. S. Geological Survey. 1965. Geological map of North America. 1:5,000,000.

189. _____________. 1970. The national atlas of the United States. Washington, D. C.: U. S. Government Printing Office. 417 pp.

190. Van Lopik, J. R., G. S. Rombie, and A. E. Pressman. 1968. Pollution surveillance by noncontact infrared techniques. Journal Water Pollution Control Federation. 40(3):425-438.

191. Veatch, J. O. and C. R. Humphrys. 1966. Water and water use terminology. Kaukauna: Thomas Printing and Publishing. 375 pp.

192. Visher, S. S. 1954. Climatic atlas of the United States. Cambridge: Harvard University Press. 403 pp.

193. Vollenweider, R. A. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters with particular reference to nitrogen and phosphorus as factors in eutrophication. Technical report prepared for the Organization for Economic Cooperation and Development. Paris, France. 159 pp.

194. Ward, J. H. Jr. 1963. Hierarchical grouping to optimize an objective function. American Statistical Association Journal. 58:236-244.

195. Watanabe, K. 1973. Polluted and turbid water masses in Osaka Bay and its vicinity revealed with ERTS-A imageries. Symposium on Significant Results obtained from the Earth Resources Technology Satellite-1. 5-9 March 1973. NASA (Goddard Space Flight Center). I(Section B):681-688.

196. Weber, C. A. 1907. Aufbau and Vegetation der Moore Norddeutschlands. Beiblatter Botanische Jahrbucker fur Systematik, Pflanzengeschichte und Pflanzengeographie. 90:19-34. Supplement to Bot. Jahrb. 40.

197. Welch, P. S. 1952. Limnology. Second edition. New York: McGraw-Hill. 538 pp.

198. Wezernak, C. T. and F. C. Polcyn. 1972. Eutrophication assessment using remote sensing techniques. Proceedings of the Eighth International Symposium on Remote Sensing of Environment. 2-6 October 1972. Ann Arbor: University of Michigan. 1:541-551.

199. Whipple, G. C. 1898. Classifications of lakes according to temperature. American Naturalist. 32(373):25-33.

200. White, P. G. 1969. Experimental results of the remote measurement of ocean color. In: Second Annual Earth Resources Aircraft Program Status Review. 16-18 September 1969. NASA Manned Spacecraft Center. Houston. 3(50):1-9.

201. Williams, L. O. and J. D. Samol. 1968. Effects on photographs of water by variation of sediment and algal content under controlled conditions. Technical Report Number 9. Office of Naval Research Contract Number N00014-67-A0102-0001. Johnson City: East Tennessee State University Remote Sensing Institute. 6 pp. + 6 pp. photographs.

202. Williams, W. T. and M. B. Dale. 1965. Fundamental problems in numerical taxonomy. Advances in Botanical Research. 2:35-68.

203. Winner, R. W. 1972. An evaluation of certain indices of eutrophy and maturity in lakes. Hydrobiologia. 40(2):223-245.

204. Work, E. A. Jr., D. S. Gilmer, and A. T. Klett. 1973. Preliminary evaluation of ERTS-1 for determining numbers and distribution of prairie ponds and lakes. In: Symposium on Significant Results obtained from the Earth Resources Technology Satellite-1. 5-9 March 1973. NASA (Goddard Space Flight Center). I(Section B):801-808.

205. Wright, F. F., G. D. Sharma, and D. C. Burbank. 1973. ERTS-1 observations of sea surface circulation and sediment transport, Cook Inlet, Alaska. In: Symposium on Significant Results obtained from the Earth Resources Technology Satellite-1. 5-9 March 1973. NASA (Goddard Space Flight Center). I(Section B):1315-1322.

206. Yarger, H. L., J. R. McCauley, G. W. James, L. M. Magnuson, and G. R. Marzolf. 1973. Water turbidity detection using ERTS-1 imagery. In: Symposium on Significant Results obtained from the Earth Resources Technology Satellite-1. 5-9 March 1973. NASA (Goddard Space Flight Center). I(Section B):651-658.

207. Yentch, C. S. 1960. The influence of phytoplankton pigments on the color of sea water. Deep Sea Research. 7:1-9.

208. ______________. 1962. Measurement of visible light absorption by particulate matter in the ocean. Limnology and Oceanography. 7:207-217.

209. Yentch, C. S. and D. W. Menzel. 1963. A method for the determination of phytoplankton chlorophyll and phaeophytin by fluorescence. Deep Sea Research. 10:221-231.

210. Zafar, A. R. 1959. Taxonomy of lakes. Hydrobiologia. 13(3): 287-299.

211. Zumberge, J. H. 1952. The lakes of Minnesota: their origin and classification. Minnesota Geological Survey Bulletin Number 35. 99 pp.

SECTION X

LIST OF ACRONYMS AND SYMBOLS

AAY: algal assay yield

ADP: automatic data processing

AIP: automatic image processing

A-space: attribute space

b&w: black and white

bit: binary digit

bpi: bits per inch

CRT: cathode ray tube

CCT: computer-compatible tape

CDC: Control Data Corporation

CHLA: chlorophyll a

COND: conductivity

cm: centimeter

°C: degrees Celsius

DN: digital number

DCS: data collection system

EBR: electron beam recorder

EPA: Environmental Protection Agency (United States)

EROS: Earth Resources Observation Systems

ERTS-1: Earth Resources Technology Satellite Number One

ESB: Eutrophication Survey Branch

GRN: Green (MSS Band 4)

GRNIR1: ratio of green to infrared-one

GRNIR2: ratio of green to infrared-two

GRNRED: ratio of green to red

GRAFPAC: standard graphic output subroutines

GSFC: Goddard Space Flight Center

ha: hectare

hz: hertz

IBM: International Business Machines

IFOV: instantaneous field of view

IPL: Image Processing Laboratory (Jet Propulsion Laboratory)

IR1: infrared-one

IR2: infrared-two

IR1IR2: ratio of infrared-one to infrared-two

ISEC: inverse of Secchi disc transparency

I-space: individual space

JPL: Jet Propulsion Laboratory

km: kilometer

l: liter

LANDSAT-1: Land Satellite One (i.e., ERTS-1)

LN: natural logarithm

LNAAY: natural log-transformed algal assay yield

LNCHLA: natural log-transformed chlorophyll a

LNCOND: natural log-transformed conductivity

LNISEC: natural log-transformed inverse of Secchi disc transparency

LNSECCHI: natural log-transformed Secchi disc transparency

LNTON: natural log-transformed total organic nitrogen

LNTPHOS: natural log-transformed total phosphorus

m: meter

MCR: mean composite rank

µg: microgram

µsec: microsecond

mg: milligram

MSS: multispectral scanner

N: number of observations

NASA: National Aeronautics and Space Administration

NERC: National Environmental Recearch Center

NES: National Eutrophication Survey

NIR: near-infrared

nm: nanometers

OD: optical density

OS: operating system

OSI: Optimum Systems Incorporated

OSU: Oregon State University

PCA: principal components anaylsis

PC1: principal component trophic state index

pixel: picture element

PMT: photomultiplier tube

PNERL: Pacific Northwest Environmental Research Laboratory

RBV: return beam vidicon

RED: red (MSS Band 5)

R-space: row space (i.e., attribute space)

REDIR1: ratio of red to infrared-one

REDIR2: ratio of red to infrared-two

SECCHI: Secchi disc transparency

SIPS: Statistical Interactive Programming System

S-matrix: similarity matrix

STORET: Storage and Retrieval number

TON: total organic nitrogen

TPHOS: total phosphorus

USGS: United States Geological Survey

VFC: video film converter

VICAR: Video Communication and Retrieval

XGRNIR1: mean of green to infrared-one ratios

XGRNIR2: mean of green to infrared-two ratios

XGRNRED: mean of green to red ratios

XIR1IR2: mean of infrared-one to infrared-two ratios

XREDIR1: mean of red to infrared-one ratios

XREDIR2: mean of red to infrared-two ratios

Δ: Euclidian distance

Δ^2: squared Euclidian distance

$\wedge$: predicted value

SECTION XI

APPENDICES

A. Trophic Indicator Data for 100 NES-sampled Lakes

B. Sampling Dates for 100 NES-sampled Lakes (1972)

C. Morphometry and Hydrology of Study Lakes

D. LANDSAT-1 MSS Models, Concatenations, Areal Relationships, and Descriptive Statistics

E. N x N Squared Euclidian Distance Matrix

F. Listing of the McKeon Cluster Analysis Program

APPENDIX A

TROPHIC INDICATOR DATA FOR 100 NES-SAMPLED LAKES

Lake Name	Serial Number	SECCHI	ISEC	COND	TPHOS	TON	CHLA	AAY
Blackduck	1	1.72	0.58	244	0.051	0.80	14.6	2.2
Bemidji	2	2.15	0.47	315	0.049	0.69	9.5	1.3
Andrusia	3	1.37	0.73	276	0.035	0.58	13.0	1.8
Wolf	4	1.19	0.84	384	0.068	0.48	17.2	1.6
Cass	5	1.88	0.53	272	0.027	0.53	9.8	0.8
Leech	6	2.17	0.46	262	0.020	0.53	6.2	0.5
Birch	7	2.44	0.41	205	0.024	0.42	7.1	1.4
Trout	8	2.81	0.36	325	0.045	0.43	7.0	1.6
Mashkenode	9	1.05	0.95	301	0.100	0.56	25.3	2.6
Whitewater	10	1.71	0.59	139	0.066	0.67	9.8	2.9
Pelican	11	1.71	0.59	88	0.033	0.39	11.4	1.3
Shagawa	12	1.77	0.57	71	0.084	0.53	11.3	4.5
Gull	13	2.32	0.43	204	0.031	0.51	12.5	2.4
Rabbit	14	2.71	0.37	276	0.036	1.25	6.7	2.0
Cranberry	15	1.18	0.85	107	0.038	0.78	30.2	0.2
Darling	16	2.56	0.39	391	0.019	0.80	11.8	0.8
Carlos	17	2.74	0.37	353	0.014	0.56	4.6	0.9
Le Homme Dieu	18	2.31	0.43	315	0.022	0.67	12.4	0.2
Minnewaska	19	1.71	0.59	638	0.035	0.90	7.6	0.4
Nest	20	1.36	0.74	353	0.050	1.03	21.4	3.8
Green	21	2.79	0.36	353	0.051	0.46	4.9	1.3
Wagonga	22	0.29	3.41	808	0.940	1.54	94.5	13.9
Clearwater	23	1.57	0.64	362	0.033	0.77	12.7	2.4
Mud (at Maple Lake)	24	0.35	2.88	530	1.893	1.31	132.3	8.5
Cokato	25	1.34	0.54	540	0.208	1.39	10.7	29.0
Buffalo	26	1.27	0.79	597	0.224	1.65	38.1	16.2
Carrigan	27	0.28	3.58	595	1.164	1.81	84.3	13.2
Silver	28	0.25	3.94	470	0.540	3.35	126.1	25.9
Minnetonka	29	1.38	0.73	361	0.070	1.45	16.6	1.2
Forest	30	2.16	0.46	273	0.024	0.61	10.5	0.2
White Bear	31	3.45	0.29	253	0.019	1.32	5.2	0.3
St. Croix	32	1.11	0.90	159	0.054	0.57	10.2	3.4
Spring	33	0.47	2.15	450	0.237	0.64	21.8	34.5
Pepin	34	0.96	1.05	417	0.187	2.13	14.9	14.0
Madison	35	0.86	1.16	305	0.064	1.24	30.4	3.8
Sakatah	36	1.89	0.53	389	0.324	1.21	10.8	14.8
Bear	37	0.28	3.58	431	0.191	1.57	61.2	5.5
Albert Lea	38	0.19	5.37	650	1.002	2.50	381.2	61.3
Yellow	39	1.49	0.67	174	0.071	0.43	13.7	3.3

APPENDIX A (continued)

TROPHIC INDICATOR DATA FOR 100 NES-SAMPLED LAKES

Lake Name	Serial Number	SECCHI	ISEC	COND	TPHOS	TON	CHLA	AAY
Wapogasset	40	1.80	0.56	198	0.053	0.45	16.6	5.5
Long	41	0.88	1.13	72	0.046	0.87	7.1	0.2
Elk	42	0.93	1.07	66	0.140	0.83	7.1	2.8
Trout	43	4.12	0.24	96	0.042	0.24	2.7	0.7
Crystal	44	8.03	0.13	50	0.007	0.15	1.5	0.2
Tainter	45	1.39	0.72	173	0.115	0.50	13.7	16.8
Shawano	46	2.00	0.50	220	0.021	0.66	11.9	0.7
Poygan	47	0.48	2.07	306	0.077	1.09	19.4	8.9
Butte des Morts	48	0.58	1.73	289	0.063	0.70	25.4	6.7
Winnebago	49	0.55	1.82	316	0.156	1.02	48.4	13.4
Round	50	3.40	0.29	323	0.018	0.60	3.5	0.2
Green	51	5.78	0.17	386	0.043	0.43	4.8	1.0
Swan	52	1.91	0.53	378	0.158	0.71	8.2	17.2
Beaver Dam	53	0.43	2.34	422	0.388	0.31	69.5	12.7
Kegonsa	54	1.10	0.91	403	0.140	0.73	30.9	8.0
Rock	55	2.32	0.43	378	0.019	0.63	8.1	0.3
Koshkonong	56	1.58	0.63	580	0.333	1.29	36.1	29.0
Lac La Belle	57	2.04	0.49	434	0.013	0.57	7.9	0.2
Oconomowoc	58	3.34	0.30	437	0.015	0.93	3.1	0.2
Okauchee	59	2.49	0.40	446	0.016	0.70	8.4	3.5
Pine	60	1.84	0.54	308	0.026	0.67	7.5	1.4
Nagawicka	61	1.30	0.77	503	0.135	0.77	12.0	21.8
Pewaukee	62	1.72	0.58	435	0.036	1.63	15.5	2.1
Tichigan	63	0.58	1.71	599	0.479	0.97	44.7	26.0
Browns	64	2.78	0.36	435	0.021	0.68	6.4	0.8
Middle	65	3.59	0.28	399	0.012	0.39	4.7	0.2
Delavan	66	1.26	0.79	451	0.144	1.02	43.9	19.9
Como	67	0.52	1.94	390	0.064	1.05	36.4	0.3
Geneva	68	3.22	0.31	386	0.015	0.59	5.8	0.3
Charlevoix	69	3.78	0.27	289	0.007	0.19	3.0	0.1
Higgins	70	6.21	0.16	231	0.040	0.13	1.1	0.1
Houghton	71	2.01	0.50	236	0.015	0.52	9.2	0.2
Pere Marquette	72	1.31	0.77	438	0.035	0.29	11.8	5.5
White	73	2.09	0.48	442	0.031	0.42	9.2	4.5
Muskegon	74	1.61	0.52	347	0.081	0.61	9.5	7.3
Fremont	75	1.48	0.68	486	0.482	3.35	28.5	44.0
Mona	76	1.23	0.82	446	0.428	0.79	27.3	31.6
Crystal	77	3.40	0.29	327	0.009	0.62	2.9	0.1
Jordan	78	1.84	0.54	416	0.187	0.84	20.5	22.2
Thornapple	79	1.45	0.69	576	0.050	0.71	14.7	4.5

APPENDIX A (continued)

TROPHIC INDICATOR DATA FOR 100 NES-SAMPLED LAKES

Lake Name	Serial Number	SECCHI	ISEC	COND	TPHOS	TON	CHLA	AAY
Strawberry	80	1.97	0.51	405	0.168	0.75	11.2	16.9
Chemung	81	2.43	0.41	402	0.037	0.83	13.5	2.7
Thompson	82	2.34	0.43	490	0.040	0.83	12.0	2.9
Ford	83	1.11	0.90	539	0.111	0.81	14.7	14.6
Union	84	1.13	0.88	510	0.055	0.51	15.7	2.7
Long	85	1.93	0.52	452	0.197	1.00	10.1	17.4
Randall	86	1.08	0.92	518	0.203	0.78	27.2	18.8
Schroon	87	3.73	0.27	51	0.005	0.16	2.1	0.1
Black	88	1.86	0.54	116	0.036	0.67	13.1	1.3
Cassadaga	89	2.57	0.39	204	0.029	0.36	9.7	4.4
Chautauqua	90	2.00	0.50	152	0.036	0.41	13.3	5.4
Conesus	91	3.19	0.31	341	0.022	0.36	9.9	0.9
Canandaigua	92	4.33	0.23	318	0.014	0.08	4.3	0.1
Keuka	93	3.57	0.28	246	0.010	0.18	5.9	6.0
Seneca	94	4.14	0.24	778	0.012	0.11	6.1	0.1
Cayuga	95	2.80	0.36	442	0.015	0.23	3.0	0.1
Owasco	96	2.71	0.37	280	0.010	0.19	8.5	0.2
Cross	97	1.36	0.74	641	0.127	0.50	19.5	3.2
Otter	98	1.14	0.88	283	0.078	0.63	13.3	1.1
Round	99	1.17	0.86	262	0.073	0.58	28.3	18.4
Saratoga	100	2.52	0.40	227	0.028	0.51	11.8	7.5

Indicator acronyms: SECCHI = Secchi disc transparency (m)[a]
ISEC = inverse of Secchi disc transparency (m^{-1})[a]
COND = conductivity (micromhos cm^{-1})[a]
TPHOS = total phosphorus (mg l^{-1})[a]
TON = total organic nitrogen (mg l^{-1})[b]
CHLA = chlorophyll a (μg l^{-1})[a]
AAY = algal assay control yield (mg dry wt)[b]

Lakes 1-38 are located in Minnesota; 39-68 are in Wisconsin; 69-86 are found in Michigan; 87-100 are in New York. The serial numbers are unique to this report.

---

[a] Mean values based on three sampling periods.

[b] Values based on composite fall sample.

APPENDIX B

SAMPLING DATES FOR 100 NES-SAMPLED LAKES (1972)

Lake Name	Serial Number	1st Sample	2nd Sample	3rd Sample	Lake Name	Serial Number	1st Sample	2nd Sample	3rd Sample
Blackduck	1	07/12	09/08	10/21	Cokato	25	06/30	08/29	10/26
Bemidji	2	07/11	09/08	10/21	Buffalo	26	06/30	08/29	10/26
Andrusia	3	07/11	09/08	10/21	Carrigan	27	06/30	08/29	10/26
Wolf	4	07/11	09/08	10/21	Silver	28	07/03	08/29	10/26
Cass	5	07/11	09/07	10/21	Minnetonka	29	06/29	09/05	10/29
Leech	6	07/11	09/08	10/21	Forest	30	06/29	08/27	11/05
Birch	7	07/12	09/03	10/24	White Bear	31	06/29	08/27	11/05
Trout	8	07/11	09/08	10/22	St. Croix	32	06/28	08/26	11/04
Mashkenode	9	07/10	09/09	10/19	Spring	33	06/28	08/26	11/04
Whitewater	10	07/06	09/02	10/25	Pepin	34	06/28	09/03	11/04
Pelican	11	07/10	09/07	10/22	Madison	35	07/01	08/30	10/29
Shagawa	12	07/08	09/07	10/22	Sakatah	36	07/01	08/30	10/29
Gull	13	07/02	09/05	10/24	Bear	37	07/01	08/30	10/29
Rabbit	14	07/02	09/04	10/24	Albert Lea	38	07/01	08/30	10/29
Cranberry	15	07/02	09/04	10/24	Yellow	39	06/26	08/27	11/03
Darling	16	07/06	09/01	10/25	Wapogasset	40	06/26	08/26	11/03
Carlos	17	07/10	09/02	10/28	Long	41	06/25	08/25	11/04
Le Homme Dieu	18	07/06	09/02	10/28	Elk	42	06/25	08/25	11/04
Minnewaska	19	07/06	09/01	10/25	Trout	43	06/25	08/23	11/04
Nest	20	07/02	08/31	10/25	Crystal	44	06/25	08/23	11/04
Green	21	07/02	08/31	10/25	Tainter	45	06/26	08/26	11/03
Wagonga	22	07/02	08/31	10/25	Shawano	46	06/22	08/24	11/08
Clearwater	23	07/03	08/29	10/27	Poygan	47	06/22	08/21	11/08
Mud (at Maple)	24	06/30	08/29	10/26	Butte des Morts	48	06/22	08/20	11/09

APPENDIX B (continued)

SAMPLING DATES FOR 100 NES-SAMPLED LAKES (1972)

Lake Name	Serial Number	1st Sample	2nd Sample	3rd Sample	Lake Name	Serial Number	1st Sample	2nd Sample	3rd Sample
Winnebago	49	06/24	08/20	11/09	Fremont	75	06/13	09/15	11/13
Round	50	06/23	08/22	11/08	Mona	76	06/13	09/19	11/14
Green	51	06/22	08/21	11/08	Crystal	77	06/15	09/17	11/14
Swan	52	06/22	08/20	11/10	Jordan	78	06/15	09/18	11/15
Beaver Dam	53	06/20	08/21	11/09	Thornapple	79	06/13	09/18	11/14
Kegonsa	54	06/22	08/20	11/10	Strawberry	80	06/17	09/19	11/13
Rock	55	06/23	08/20	11/10	Chemung	81	06/16	09/19	11/15
Koshkonong	56	06/22	08/17	11/10	Thompson	82	06/16	09/19	11/15
Lac La Belle	57	06/23	08/19	11/09	Ford	83	06/16	09/19	11/13
Oconomowoc	58	06/21	08/19	11/11	Union	84	06/14	09/16	11/12
Okauchee	59	06/21	08/19	11/10	Long	85	06/13	09/17	11/12
Pine	60	06/21	08/19	11/09	Randall	86	06/14	09/16	11/12
Nagawicka	61	06/21	08/19	11/10	Schroon	87	06/01	07/25	10/10
Pewaukee	62	06/21	08/19	11/10	Black	88	05/20	07/25	10/10
Tichigan	63	06/21	08/17	11/10	Cassadaga	89	05/26	07/27	10/13
Browns	64	06/21	08/16	11/10	Chatauqua	90	05/26	07/27	10/12
Middle	65	06/22	08/19	11/10	Conesus	91	05/27	07/27	10/13
Delavan	66	06/23	08/17	11/10	Canandaigua	92	05/27	07/21	10/14
Como	67	06/21	08/16	11/10	Keuka	93	05/27	07/21	10/14
Geneva	68	06/21	08/16	11/10	Seneca	94	05/16	07/23	10/14
Charlevoix	69	06/16	09/14	11/12	Cayuga	95	05/16	07/23	10/13
Higgins	70	06/15	09/16	11/12	Owasco	96	05/28	07/24	10/12
Houghton	71	06/15	09/20	11/14	Cross	97	05/28	07/24	10/13
Pere Marquette	72	06/17	09/18	11/13	Otter	98	05/17	07/24	10/13
White	73	06/13	09/18	11/14	Round	99	05/28	07/25	10/10
Muskegon	74	06/13	09/19	11/14	Saratoga	100	05/15	07/25	10/11

APPENDIX C

MORPHOMETRY AND HYDROLOGY OF STUDY LAKES[a]

Lake Name	Serial Number	Area (ha)	Mean Depth (m)	Maximum Depth (m)	Volume $(m^3) \times 10^6$	Shore Line (km)	Retention Time[b]
Blackduck	01	1,110	4.6	8.5	50.733	16.0	4.3 y
Bemidji	02	2,598	9.6	23.2	253.407	23.8	268 d
Andrusia	03	614	7.9	18.3	48.426	14.7	47 d
Wolf	04	425	8.5	17.7	36.299	12.1	37 d
Cass	05	6,312	7.6	36.6	480.934	63.1	313 d
Leech	06	45,326	4.7	45.7	214.132		5.2 y
Birch	07	519	3.1	13.7	15.826	22.7	
Trout	08	765	15.2	41.2	116.564	21.7	17.4 y
Mashkenode	09	41	2.1	4.3	0.872	3.06	9 d
Whitewater	10	490	6.1	22.3	29.701	21.1	
Pelican	11	4,429	3.7	11.6	162.005	56.1	5.0 y
Shagawa	12	955	5.7	14.7	54.436	29.0	0.9 y
Gull	13	3,812	9.1	26.2	348.508	64.2	2.9 y
Rabbit	14	340	3.7	12.8	43.520	9.81	
Cranberry	15	8.1	3.4	10.4	0.275		
Darling	16	386	6.2	18.9	23.888	10.8	
Carlos	17	1,020	13.1	49.7	133.660	19.2	3.7 y
Le Homme Dieu	18	706	6.4	25.9	45.175	15.3	7.9 y
Minnewaska	19	2,877	6.0	9.8	171.893	29.6	12.7 y
Nest	20	382	4.6	12.2	17.485		190 d
Green	21	2,187	6.4	33.5	140.032	19.8	3.7 y
Wagonga	22	654	1.2	4.6	7.978	20.9	1.3 y
Clearwater	23	1,288	5.2	22.9	66.724	27.9	1.4 y
Mud (at Maple Lake)	24						

APPENDIX C (continued)

MORPHOMETRY AND HYDROLOGY OF STUDY LAKES

Lake Name	Serial Number	Area (ha)	Mean Depth (m)	Maximum Depth (m)	Volume $(m^3) \times 10^6$	Shore Line (km)	Retention Time
Cokato	25	220	7.6	15.2	16.775	7.15	413 d
Buffalo	26	611	4.2	9.1	27.007	9.25	1.4 y
Carrigan	27	66	0.9	2.4	0.594		
Silver	28	170	1.2	2.1	2.040	6.87	3.5 y
Minnetonka	29	5,855	4.3	27.8	401.727	175.0	15 y
Forest	30	893	3.4	11.3	30.204	23.1	6.5 y
White Bear	31	1,077	6.9	24.4	74.152	21.6	
St. Croix	32	3,322	8.7	23.8	291.619		23 d
Spring	33	2,392		3.1		33.8	
Pepin	34	10,118	5.1	17.1	514.979		9 d
Madison	35	541	4.0	18.0	17.847	15.8	3.3 y
Sakatah	36	497	2.1	3.7	7.607		44 d
Bear	37	556		1.1			
Albert Lea	38	985	1.1	1.8	10.591	36.0	73 d
Yellow	39	926	5.8	9.8	53.330	11.3	
Wapogasset	40	480	5.2	9.8	25.248		194 d
Long	41	169	3.4	16.5	5.632		15 d
Elk	42	36	1.8	6.4	0.691		2 d
Trout	43	1,544	11.7	35.1	180.276	30.6	
Crystal	44	36	9.8	21.0	3.552	2.25	---c
Tainter	45	709	4.0	11.3	27.806		45 d
Shawano	46	2,491	3.2	10.7	80.231	26.6	1.5 y
Poygan	47	4,449	2.1	3.4	94.305		13 d
Butte des Morts	48	3,584	1.8	2.7	65.550		6 d
Winnebago	49	55,730	4.0	6.4	2,208.184	116.9	210 d
Round	50	5.7	5.7	17.1	0.321		
Green	51	2,972	31.7	71.9	939.021	34.1	20.7 y

APPENDIX C (continued)

MORPHOMETRY AND HYDROLOGY OF STUDY LAKES

Lake Name	Serial Number	Area (ha)	Mean Depth (m)	Maximum Depth (m)	Volume (m^3) x 10^6	Shore Line (km)	Retention Time
Swan	52	164	9.8	25.0	15.908		179 d
Beaver Dam	53	2,671	1.4	3.4	37.840	63.7	155 d
Kegonsa	54	1,099	5.2	8.8	58.234	15.4	139 d
Rock	55	555	4.9	17.1	26.325	14.2	3.6 y
Koshkonong	56	4,241	1.5	2.1	68.829	48.9	24 d
Lac la Belle	57	452	4.7	14.0	21.080	14.0	8 m
Oconomowoc	58	318	6.3	18.9	20.043	11.3	
Okauchee	59	451	9.5	28.7	40.320	24.1	10 m
Pine	60	285	11.8	25.9	33.448	11.8	
Nagawicka	61	415	10.1	27.4	41.147	13.8	1.5 y
Pewaukee	62	1,009	3.1	13.7	45.698	22.1	4.2 y
Tichigan	63	450	1.8	19.2	8.096	20.0	19 d
Browns	64	160	2.4	13.4	3.867	8.04	
Middle	65	72	4.6	13.7	3.293	8.53	
Delavan	66	718	7.6	17.1	54.810	28.5	2.8 y
Como	67	383	1.2	2.7	4.795	13.5	1.6 y
Geneva	68	2,130	18.6	41.2	395.928	32.5	29.9 y
Charlevoix	69	6,985	16.8	37.2	1,170.944	54.1	3.2 y
Higgins	70	3,885	14.9	41.2	580.230		15.6 y
Houghton	71	8,112	2.3	6.4	187.901	49.6	1.3 y
Pere Marquette	72	224		11.6			
White	73	1,040	6.7	21.3	71.468	20.8	56 d
Muskegon	74	1,680	7.0	21.0	120.295	18.8	23 d
Fremont	75	320	10.1	26.8	32.157	8.66	1.9 y
Mona	76	281	4.0	12.8	11.487	18.6	76 d
Crystal	77	293		21.3			

APPENDIX C (continued)

MORPHOMETRY AND HYDROLOGY OF STUDY LAKES

Lake Name	Serial Number	Area (ha)	Mean Depth (m)	Maximum Depth (m)	Volume $(m^3) \times 10^6$	Shore Line (km)	Retention Time
Jordan	78	174	7.3	17.7	12.995	7.19	304 d
Thornapple	79	166	4.3	9.5	7.063		11 d
Strawberry	80	104	6.7	15.2	7.006	6.34	13.2 d
Chemung	81	126	8.5	21.3	10.821	7.93	4.2 y
Thompson	82	106	2.7	15.8	2.909	7.35	152 d
Ford	83	425	4.4	11.9	18.521		15.2 d
Union	84	213	0.9	4.3	1.943	23.2	2 d
Long	85	85	5.2	12.5	4.425		31 d
Randall	86	208	5.5	14.9	11.263	5.89	41 d
Schroon	87	1,671	14.3	46.3	239.315	39.9	153 d
Black	88	3,380	2.7	5.2	92.718	92.7	0.1 y
Cassadaga	89	85	3.1	8.8	2.603	8.21	4 m
Chautauqua	90	5,720	6.7	23.5	392.266	68.3	1.4 y
Conesus	91	1,347	11.5	18.0	154.760	29.7	2.3 y
Canandaigua	92	4,300	39.0	83.5	1,677.377	57.8	15 y
Keuka	93	4,740	22.4	56.7	1,063.356	94.0	7.8 y
Seneca	94	17,252	88.4	188.4	15,249.165	121.3	33.1 y
Cayuga	95	17,198	52.4	132.6	9,375.141	136.5	10.9 y
Owasco	96	2,746	29.3	54.0	802.997	39.8	
Cross	97	881	5.5	16.8	49.339	20.0	7 d
Otter	98	114				5.86	
Round	99	127				4.35	
Saratoga	100	1,632	7.9	29.3	129.308	37.1	150 d
Winona	101	73	1.2	2.4	0.876	2.74	1.3 y
Trace	102						
Calhoun	103	170	8.2	25.0	13.940		

APPENDIX C (continued)

MORPHOMETRY AND HYDROLOGY OF STUDY LAKES

Lake Name	Serial Number	Area (ha)	Mean Depth (m)	Maximum Depth (m)	Volume (m^3) x 10^6	Shore Line (km)	Retention Time
Big Stone	104	5,103	3.4	4.9	17.35	96.4	1.6 y
Zumbro	105	345					
Oneida	106	20,721		16.7			
Canadarago	107						
Mendota	108	3,983					
Monona	109	1,350					
Waubesa	110	855					
Cottonwood	111	150	1.6	2.4	0.240	5.63	347 d
Maple	241	240	5.8	23.2	13.920		

---

[a] This table has been compiled from information contained in the files of the Eutrophication Survey Branch, Pacific Northwest Environmental Research Laboratory (NERC-Corvallis).

[b] y = year, m = month, d = day

[c] Seepage lake.

APPENDIX D

LANDSAT-1 MSS MODELS, CONCATENATIONS, AREAL RELATIONSHIPS AND DESCRIPTIVE STATISTICS

This appendix contains information relevant to each LANDSAT-1 MSS Frame examined during the investigation. It is divided into a series of subappendices, one for each frame or pair of frames. Frames in juxtaposition on the same flightline are treated as one. Each subappendix is in turn divided into five sections:

Section D_.1. Regression Models and Correlation Coefficients

Section D_.2. Three-dimensional Color Ratio Model

Section D_.3. Concatenation of Extracted Lakes

Section D_.4. MSS-Lake Surface Area Relationships

Section D_.5. Lake MSS Descriptive Statistics

APPENDIX D1. 9 August 1972 (1017-16091, 1017-16093)

Section D1.1. Regression Models and Correlation Coefficients

The regression models for the prediction of Secchi disc transparency and chlorophyll a are in Section VI along with the coefficients of correlation between the MSS data (colors and color ratios), the trophic indicators and the multivariate trophic state index. The model for the prediction of trophic state is in Section VII.

Section D1.2. Three-dimensional Color Ratio Model

The color ratio model is in Section VII (Figure 33).

Section D1.3. Concatenation of Extracted Lakes

The concatenation of lakes extracted from Frame 1017-16093 is in Section V; the Frame 1017-16091 concatenation is in this appendix (Figure D1-1).

Section D1.4. MSS-Lake Surface Area Relationships

The estimates of lake surface area using MSS data are in Section VI (Table 16).

Section D1.5. Lake MSS Descriptive Statistics

The MSS statistics for Frame 1017-16093 are in Table D1-1 and those for Frame 1017-16091 are in Table D1-2.

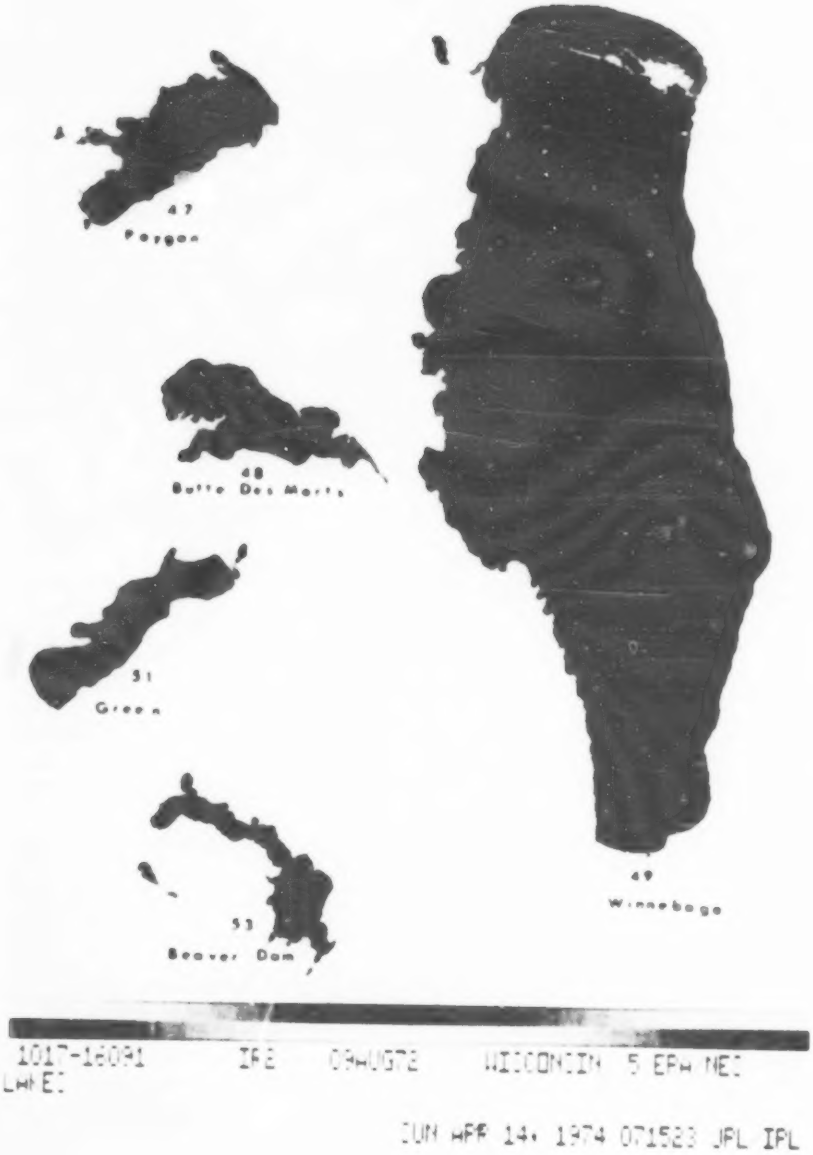

47
Poygan
48
Butte Des Morts
51
Green
53
Beaver Dam
49
Winnebago
1017-16091 IR2 09AUG72 WISCONSIN 5 EPA NES
LAKES
SUN APR 14, 1974 071523 JPL IPL

Figure D1-1. IR2 concatenation of five Wisconsin lakes extracted from Frame 1017-16091 (9 August 1972). The images have not been skewed to correct for geometric distortions. Cloud cover is evident over the northern (upper) end of Lake Winnebago.

TABLE D1-1. MSS DESCRIPTIVE STATISTICS FOR 15 WISCONSIN LAKES EXTRACTED FROM FRAME 1017-16093 (9 AUGUST 1972)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 MSS Bands			
			Green	Red	IR1	IR2
Kegonsa	54	2,675	50.18[a]	30.08	24.38	8.34
			1.63[b]	1.50	3.30	5.24
Rock	55	1,009	38.86	19.39	13.62	5.10
			3.27	3.07	3.38	3.74
Koshkonong	56	9,247	46.85	31.15	27.95	10.08
			1.81	2.45	2.93	2.89
Lac La Belle	57	944	43.30	24.27	15.11	5.69
			4.81	4.07	3.35	3.73
Oconomowoc	58	652	39.87	19.99	14.46	6.35
			4.90	4.27	4.48	4.72
Okauchee	59	871	36.78	19.70	14.35	6.07
			1.73	2.17	4.27	4.68
Pine	60	568	36.54	16.99	13.04	5.66
			2.89	2.70	3.95	4.58
Nagawicka	61	751	42.46	23.85	17.06	6.12
			2.78	1.83	3.71	3.94
Pewaukee	62	1,996	37.35	20.75	16.19	6.36
			2.54	2.34	4.44	4.01
Tichigan	63	689	40.78	25.56	23.21	10.47
			3.06	1.67	4.28	5.26
Browns	64	309	36.23	19.06	15.78	7.17
			2.59	2.87	3.99	4.63
Middle	65	117	36.49	18.54	17.38	9.35
			2.77	3.27	6.53	6.91
Delavan	66	1,541	45.42	25.39	22.07	8.35
			2.62	1.66	3.00	3.98
Como	67	703	47.86	30.27	22.51	8.62
			5.20	4.24	3.25	4.39
Geneva	68	4,543	39.42	18.53	13.71	5.69
			2.12	2.16	2.81	3.25

---

[a] Mean DN value for the lake.

[b] Standard deviation for the lake pixels.

TABLE D1-2. MSS DESCRIPTIVE STATISTICS FOR 5 WISCONSIN LAKES EXTRACTED FROM FRAME 1017-16091 (9 AUGUST 1972)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 MSS Bands			
			Green	Red	IR1	IR2
Poygan	47	9,177	46.05[a]	29.50	23.62	9.55
			4.82[b]	5.07	5.25	5.24
Butte des Morts	48	7,395	42.99	26.74	23.08	8.25
			2.55	1.83	2.78	3.59
Winnebago	49	114,186	42.38	24.95	20.86	6.65
			3.22	2.67	5.50	3.92
Green	51	6,613	36.90	17.03	12.12	4.59
			2.00	2.32	3.21	3.18
Beaver Dam	53	5,162	37.57	22.76	20.12	7.48
			2.09	2.00	4.24	4.57

[a] Mean DN value for the lake.

[b] Standard deviation of the lake DN values.

APPENDIX D2. 28 August 1972 (1036-16152)

Section D2.1. Regression Models and Correlation Coefficients

No models were developed because the sample size is insufficient; only three NES-sampled lakes were extracted from the frame. The three lakes (Rock, Kegonsa, and Koshkonong) have higher mean DN levels than on 9 August 1972, but have maintained their relative positions.

Section D2.2. Three-dimensional Color Ratio Model

No model was constructed.

Section D2.3. Concatenation of Extracted Lake

The concatenation of extracted lakes is displayed as Figure D2-1.

Section D2.4. MSS-Lake Surface Area Relationships

The estimates of lake surface using the MSS pixel counts and a conversion factor of 0.48 (1 pixel = 0.48 hectares) are in Table D2-1.

Section D2.5. Lake MSS Descriptive Statistics

The MSS statistics are in Table D2-2.

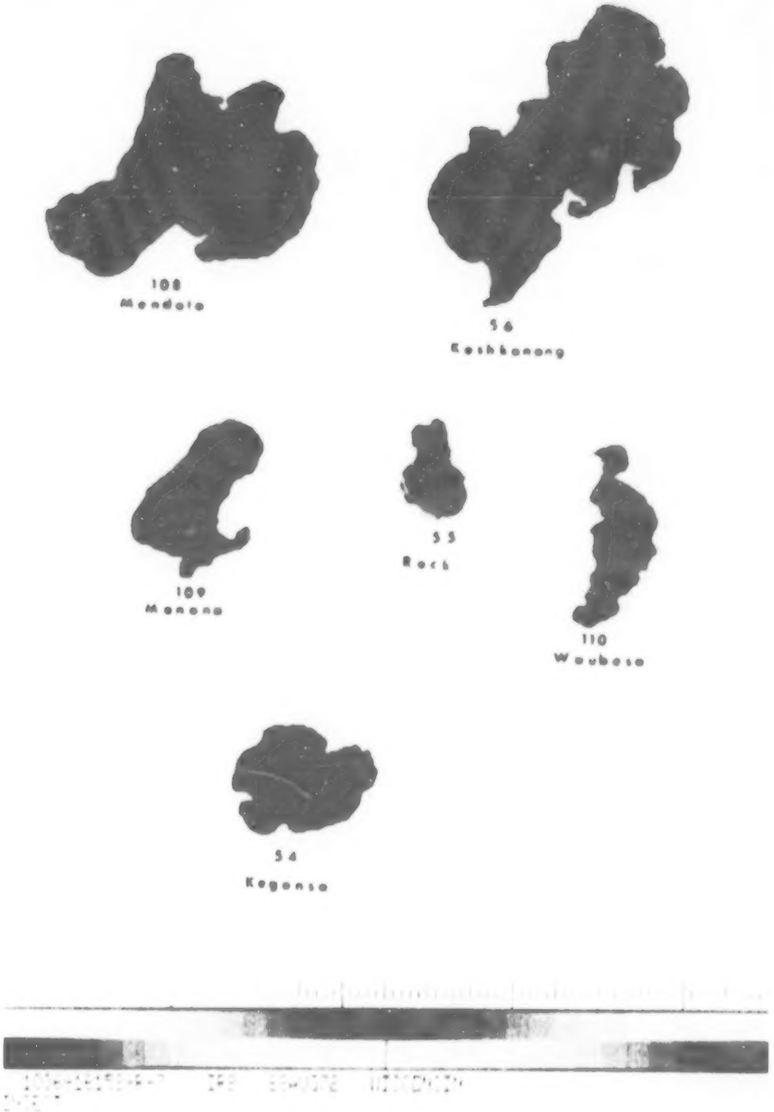

108
Mendota
56
Koshkonong
109
Monona
55
Rock
110
Waubesa
54
Kegonsa

Figure D2-1. IR2 concatenation of six Wisconsin lakes extracted from Frame 1036-16152 (28 August 1972).

TABLE D2-1. AREAL ASPECTS OF 6 WISCONSIN LAKES EXTRACTED FROM FRAME 1036-16152 (28 AUGUST 1972)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 Lake Area (ha)	Map Lake Area (ha)	Map Area:LANDSAT-1 Area Ratio
Kegonsa	54	2,805	1,340.8[a]	1,099.2	0.820
Rock	55	1,039	496.6[a]	554.8	1.117
Koshkonong	56	9,364	4,476.0[a]	4,241.5	0.948
Mendota	108	8,460	4,043.9	3,937.7	0.974
Monona	109	2,729	1,304.5	1,349.7	1.035
Waubesa	110	1,938	926.4	855.1	0.923

[a] The estimated areas of these lakes using the MSS pixel counts from Frame 1017-16093 are, respectively: 1,277.4 hectares, 481.8 hectares, and 4,415.9 hectares.

TABLE D2-2. MSS DESCRIPTIVE STATISTICS FOR 6 WISCONSIN LAKES EXTRACTED FROM FRAME 1036-16152 (28 AUGUST 1972)

Lake Name	Serial Number	Pixel Count		LANDSAT-1 MSS Bands		
			Green	Red	IR1	IR2
Kegonsa	54	2,805	46.97[a]	26.62	17.88	6.57
			2.01[b]	1.40	2.64	3.41
Rock	55	1,039	42.90	22.93	15.22	6.78
			2.38	1.74	3.92	4.49
Koshkonong	56	9,364	43.47	27.82	22.23	8.19
			2.72	1.64	2.55	3.15
Mendota	108	8,460	40.07	21.71	13.88	5.24
			2.01	1.83	2.97	3.31
Monona	109	2,729	39.24	21.84	14.29	6.05
			2.84	2.17	3.38	3.70
Waubesa	110	1,938	46.78	26.50	20.28	7.92
			4.01	2.07	3.08	4.03

[a] Mean DN value for the lake.

[b] Standard deviation of the lake DN values.

APPENDIX D3. 11 June 1973 (1323-16100, 1323-16094)

Section D3.1. Regression Models and Correlation Coefficients

The regression model for the prediction of trophic state is found in Section VII; it is of little practical value.

Section 3.2. Three-dimensional Color Ratio Model

The color ratio model is in Section VII (Figure 34).

Section 3.3. Concatenations of Extracted Lakes

The 23 lakes extracted from the frames are displayed in the form of two concatenations, Figures D3-1 and D3-2. The fragmented appearance of Lake Geneva is a result of cloud cover. Lake Winnebago is partially truncated, a consequence of separating the continuous MSS strip into discrete frames. Cloud cover is responsible for the mottled appearance of Lake Poygan. Middle Lake has not been excised from the Lauderdale Lakes as was the case for 9 August 1972.

Section D3.4. MSS-Lake Surface Area Relationships

The estimates of lake surface area using the MSS pixel count are found in Table D3-1. Area estimates have not been determined for truncated water bodies or those partially covered by clouds.

Section D3.5. Lake MSS Descriptive Statistics

The MSS statistics are in Table D3-2.

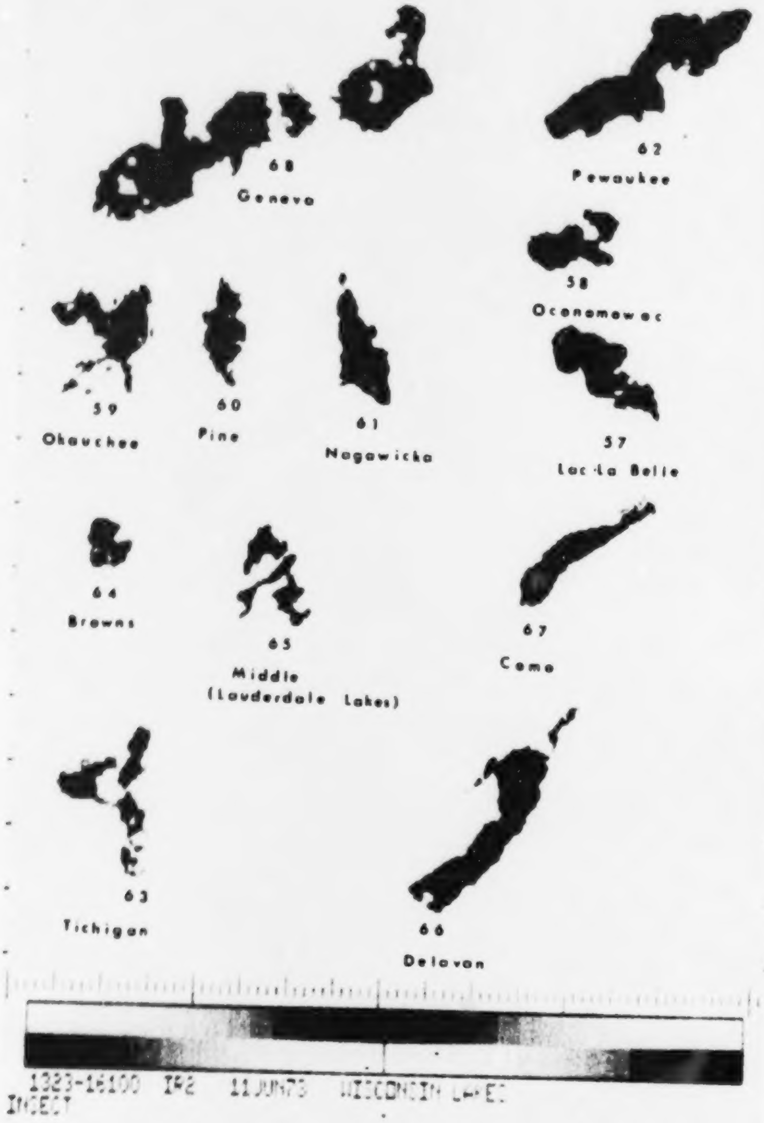

68
Geneva
62
Pewaukee
58
Oconomowoc
59
Okauchee
60
Pine
61
Nagawicka
57
Lac La Belle
64
Browns
65
Middle
(Lauderdale Lakes)
67
Como
63
Tichigan
66
Delavan
1323-16100 IR2 11JUN73 WISCONSIN LAKES
INSECT

Figure D3-1. IR2 concatenation of 12 Wisconsin lakes extracted from Frame 1323-16100 (11 June 1973). The 11 other lakes extracted from the frame are in Figure D3-2.

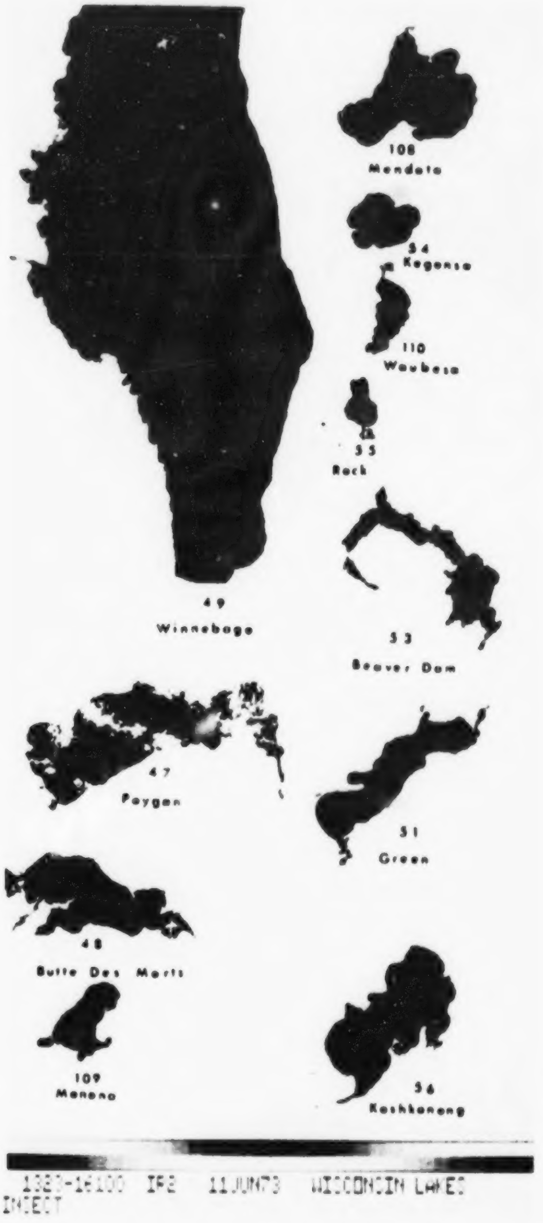

108
Mendota
54
Kegonsa
110
Waubesa
55
Rock
49
Winnebago
53
Beaver Dam
47
Poygan
51
Green
48
Butte Des Morts
109
Monona
56
Koshkonong
1323-16100 IR2 11JUN73 WISCONSIN LAKES
INJECT

Figure D3-2. IR2 concatenation of 11 Wisconsin lakes extracted from Frame 1323-16100 (11 June 1973). The other 12 lakes extracted from the frame are in Figure D3-1.

TABLE D3-1. AREAL ASPECTS OF 23 WISCONSIN LAKES EXTRACTED FROM FRAMES 1323-16094 and 1323-16100 (11 JUNE 1973)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 Lake Area (ha)	Map Lake Area (ha)	Map Area:LANDSAT-1 Area Ratio
Poygan	47	11,829	5,648.9	4,448.5	-----[a]
Butte Des Morts	48	8,053	3,845.3	3,584.4	0.932
Winnebago	49	98,821	47,206.8	55,730.4	1.181[b]
Green	51	6,742	3,220.7	2,972.9	0.923
Beaver Dam	53	5,485	2,618.8	2,671.0	1.010
Kegonsa	54	2,706	1,292.7	1,099.2	0.850
Rock	55	1,127	538.4	554.8	1.031
Koshkonong	56	9,516	4,545.8	4,241.3	0.933
Lac La Belle	57	939	448.6	452.1	1.008
Oconomowoc	58	627	299.5	317.7	1.061
Okauchee	59	928	443.3	450.8	1.017
Pine	60	550	262.7	284.5	1,083
Nagawicka	61	775	370.2	415.2	1.122
Pewaukee	62	1,982	945.8	1,008.9	1.066
Tichigan	63	707	337.7	449.8	1.332
Browns	64	304	145.2	160.3	1.104
Middle	65	563	268.9	337.6	1.254[c]
Delavan	66	1,517	724.7	717.9	0.991
Como	67	740	353.5	383.0	1.084
Geneva	68	3,555	1,698.2	2,129.5	-----[d]
Mendota	108	8,488	4,054.7	3,937.7	0.971
Monona	109	2,791	1,333.3	1,349.7	1.012
Waubesa	110	1,882	889.0	855.1	0.951

[a] The extracted image includes Lake Winneconne and substantial cloud cover.
[b] The northern end of the lake is outside the sensor field of view.
[c] The Lauderdale lakes complex was extracted and treated as a single lake.
[d] The presence of cloud cover has resulted in the low LANDSAT-1 area estimate.

TABLE D3-2. MSS DESCRIPTIVE STATISTICS FOR 23 WISCONSIN LAKES EXTRACTED FROM FRAME 1323-16100 (11 JUNE 1973)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 MSS Bands			
			Green	Red	IR1	IR2
Poygan	47	11,829	50.53	33.74	25.52	13.95
			4.97	5.24	5.89	5.69
Butte des Morts	48	8,053	47.28	30.78	22.83	11.47
			2.83	2.73	4.06	4.14
Winnebago	49	98,821	49.43	32.87	20.14	8.80
			2.98	3.01	2.65	2.80
Green	51	6,742	43.53	23.59	16.93	7.75
			2.59	2.67	3.67	3.75
Beaver Dam	53	5,485	51.55	34.55	27.40	13.25
			1.99	2.57	3.34	3.75
Kegonsa	54	2,706	49.01	29.20	19.67	9.18
			2.48	2.03	3.50	3.49
Rock	55	1,127	50.02	29.41	22.14	11.66
			3.07	2.21	3.35	3.73
Koshkonong	57	9,516	51.94	36.81	25.61	11.26
			2.40	3.31	2.97	3.43
Lac La Belle	57	939	52.02	32.55	22.49	11.37
			4.28	4.34	3.49	3.92
Oconomowoc	58	627	46.24	26.80	20.38	10.65
			3.68	3.15	3.72	4.09
Okauchee	59	928	49.49	31.32	22.68	11.75
			2.49	2.28	4.13	4.69
Pine	60	550	51.83	27.97	21.03	10.99
			2.45	2.20	3.47	4.20
Nagawicka	61	775	46.71	27.70	23.09	11.77
			2.65	2.18	5.17	4.74
Pewaukee	62	1,982	53.19	32.02	24.20	12.08
			5.65	3.70	4.24	4.15
Tichigan	63	707	48.19	31.03	24.85	13.54
			2.82	2.37	5.11	5.04
Browns	64	304	50.40	29.75	22.03	12.11
			2.49	2.37	3.84	4.31
Middle	65	563	48.94	28.25	22.74	13.05
			3.04	2.46	5.31	5.22
Delavan	66	1,517	51.76	31.16	24.30	12.29
			3.05	2.72	5.01	4.10
Como	67	740	60.33	40.42	28.28	14.07
			5.56	5.37	4.02	4.22
Geneva	68	3,555	54.15	31.44	23.63	13.26
			5.71	4.87	5.23	4.90
Mendota	108	8,488	51.01	28.74	19.80	8.59
			2.58	2.36	3.19	3.16
Monona	109	2,791	49.27	27.68	19.81	9.36
			3.08	2.39	4.39	3.90
Waubesa	110	1,882	47.56	27.53	21.31	10.38
			2.76	2.16	6.56	5.28

APPENDIX D4. 17 July 1973 (1359-16091, 1359-16094)

Section D4.1. Regression Models and Correlation Coefficients

The regression model for the prediction of the multivariate trophic state index is in Section VII.

Section D4.2. Three-dimensional Color Ratio Model

The MSS color ratio model is in Section VII (Figure 35). It is very similar in appearance to the model constructed from 9 August 1972 data.

Section D4.3. Concatenations of Extracted Lakes

Eighteen of the 21 lakes extracted from the frames are found in Figures D4-1 and D4-2. Lake Winnebago is common to both frames. Cloud interference is noted over some of the lakes.

Section D4.4. MSS-Lake Surface Area Relationships

The estimates of lake surface area using the MSS pixel counts are found in Table D4-1.

Section D4.5. Lake MSS Descriptive Statistics

The MSS statistics for Frame 1359-16091 are in Table D4-2 and those for Frame 1359-16094 are in Table D4-3.

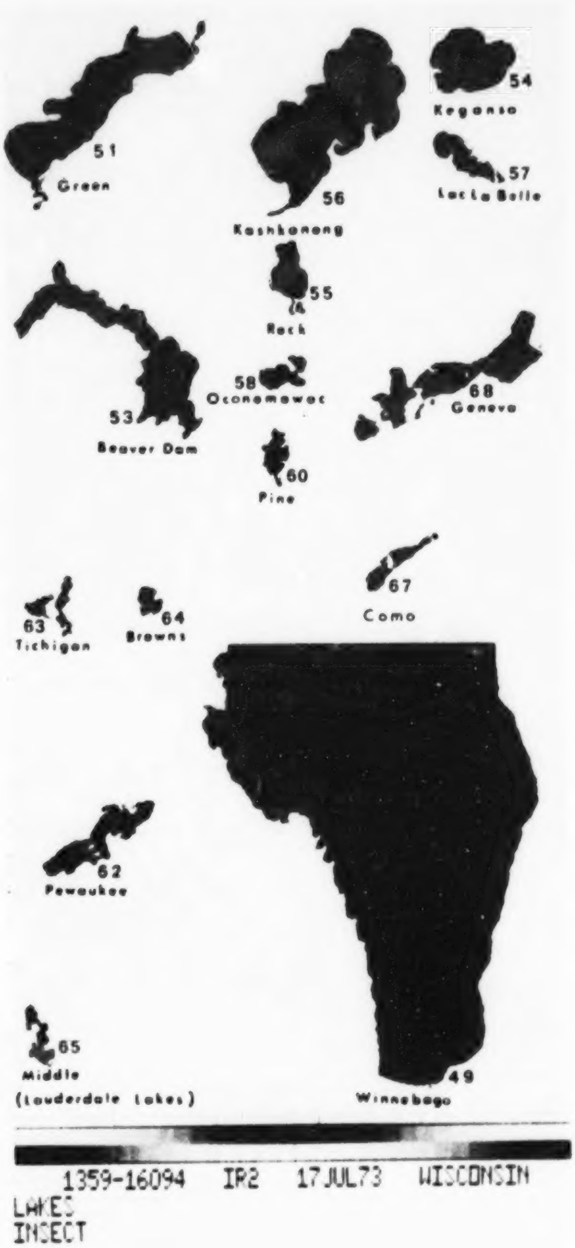

51
Green
56
Koshkonong
54
Kegonsa
57
Lac La Belle
55
Rock
53
Beaver Dam
58
Oconomowoc
68
Geneva
60
Pine
67
Como
63
Tichigan
64
Browns
62
Pewaukee
65
Middle
(Lauderdale Lakes)
49
Winnebago
1359-16094 IR2 17JUL73 WISCONSIN
LAKES
INSECT

Figure D4-1. IR2 concatentation of 15 Wisconsin lakes extracted from Frame 1359-16094 (17 July 1973).

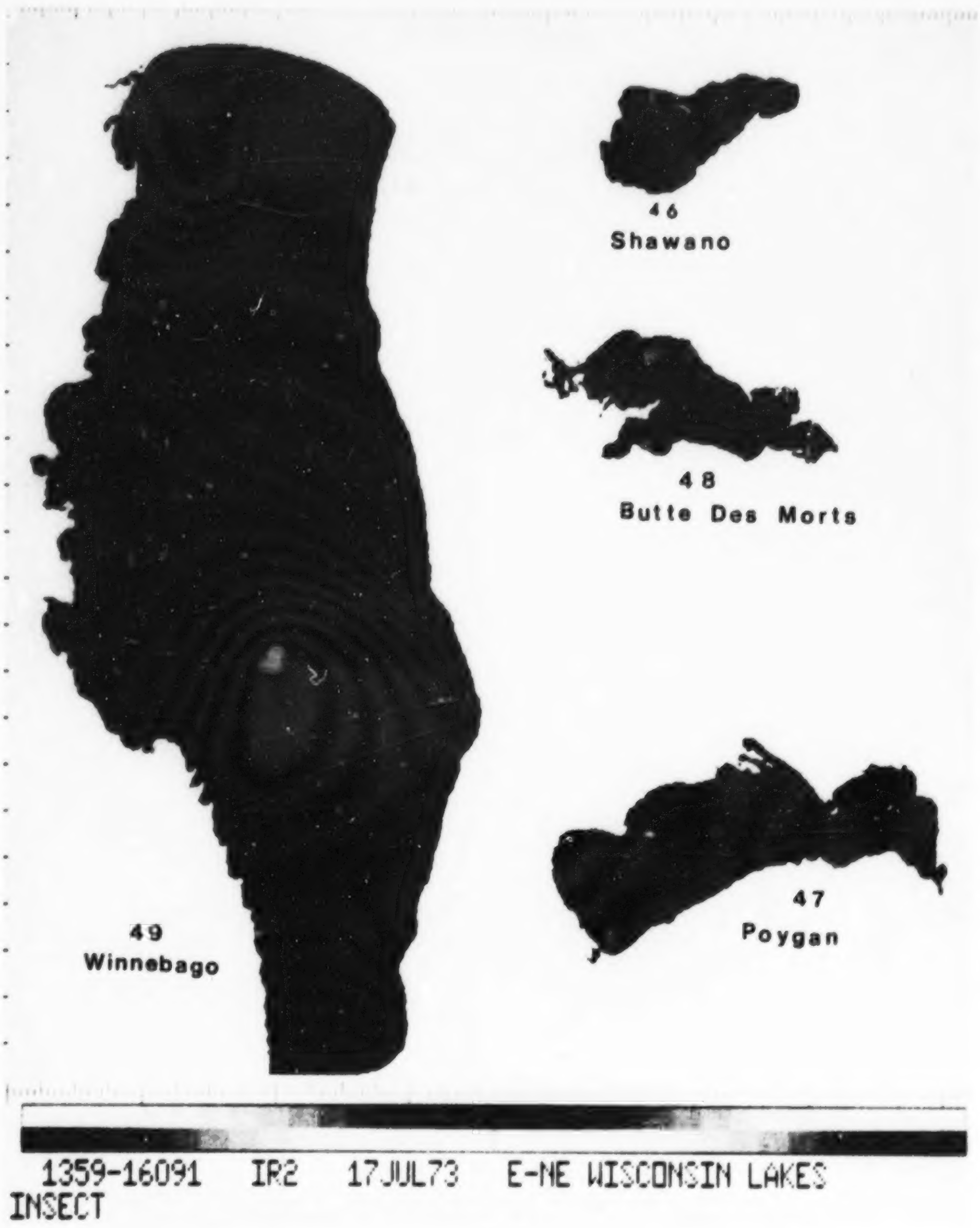

46
Shawano
48
Butte Des Morts
47
Poygan
49
Winnebago
1359-16091 IR2 17JUL73 E-NE WISCONSIN LAKES
INSECT

Figure D4-2. IR2 concatenation of 4 Wisconsin lakes extracted from Frame 1359-16091 (17 July 1973).

TABLE D4-1. AREAL ASPECTS OF 21 WISCONSIN LAKES EXTRACTED FROM FRAMES 1359-16091 and 1359-16094 (17 JULY 1973)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 Lake Area (ha)	Map Lake Area (ha)	Map Area:LANDSAT-1 Area Ratio
Shawano	46	5,263	2,514.1	2,491.3	0.991
Poygan	47	15,836	7,564.9	4,448.5	-----[a]
Butte des Morts	48	7,600	3,630.5	3,584.4	0.987
Winnebago	49	112,887	53,926.1	55,730.4	1.034
Green	51	6,594	3,150.0	2,972.9	0.944
Beaver Dam	53	5,057	2,415.7	2,671.0	1.106
Kegonsa	54	2,716	1,297.4	1,099.2	0.847
Rock	55	1,102	526.4	554.8	1.054
Koshkonong	56	9,029	4,313.2	4,241.3	0.983
Lac La Belle	57	927	442.8	452.1	1.021
Oconomowoc	58	613	292.8	317.7	1.085
Okauchee	59	791	377.9	450.8	1.193
Pine	60	563	269.0	284.5	1.058
Nagawicka	61	505	241.2	415.2	-----[b]
Pewaukee	62	1,851	884.2	1,008.9	1.141[b]
Tichigan	63	561	268.0	449.8	-----[c]
Browns	64	317	151.4	160.3	1.059
Middle	65	630	301.0	337.6	1.122[d]
Delavan	66	1,487	710.3	717.9	1.011
Como	67	615	293.8	383.0	1.304[b]
Geneva	68	3,684	1,759.9	2,129.5	1.210[b]

---

[a] Pixel count includes Lake Winneconne.

[b] Cloud interference.

[c] A portion of the lake body was truncated during the extraction process.

[d] Includes the entire Lauderdale lake complex.

TABLE D4-2. MSS DESCRIPTIVE STATISTICS FOR 4 WISCONSIN LAKES EXTRACTED FROM FRAME 1359-16901 (17 JULY 1973)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 MSS Bands Green	Red	IR1	IR2
Poygan	47	15,836	56.74 2.96	39.27 3.45	32.09 4.37	16.74 3.32
Butte des Morts	48	7,600	53.31 3.04	34.49 3.45	28.99 4.51	13.44 3.67
Winnebago	49	112,887[a]	51.41 3.29	32.40 3.31	23.94 3.62	10.74 3.35
Shawano	46	5,263	46.38 2.69	28.38 2.89	20.61 3.57	10.16 3.54

[a] Southern end of Lake Winnebago is outside the sensor field of view.

TABLE D4-3. MSS DESCRIPTIVE STATISTICS FOR 17 WISCONSIN LAKES EXTRACTED FROM FRAME 1359-16094 (17 JULY 1973)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 MSS Bands			
			Green	Red	IR1	IR2
Green	51	6,594	52.65	29.40	21.00	10.69
			2.27	2.10	3.37	3.35
Beaver Dam	53	5,057	56.88	38.74	33.17	14.70
			2.40	2.72	3.80	3.40
Kegonsa	54	2,716	60.79	36.33	20.71	13.97
			2.59	2.25	4.06	3.83
Rock	55	1,102	51.85	30.38	21.99	11.42
			3.04	3.13	4.44	4.37
Koshkonong	56	9,029	54.72	37.93	29.03	12.26
			2.79	3.52	3.89	3.21
Lac La Belle	57	927	56.55	34.60	23.29	12.00
			5.43	5.24	4.48	4.64
Oconomowoc	58	613	49.58	28.35	21.04	10.97
			3.45	3.31	3.86	4.17
Okauchee	59	791	50.77	30.91	23.42	12.99
			3.57	3.46	5.13	5.27
Pine	60	563	53.20	28.25	22.35	12.95
			4.07	3.37	4.87	5.51
Nagawicka	61	505	51.92	31.30	25.04	13.91
			6.11	5.26	5.73	5.46
Pewaukee	62	1,851	52.27	31.26	24.50	13.04
			3.75	2.88	5.26	4.41
Tichigan	63	561	52.04	33.00	28.48	15.30
			4.75	3.60	5.43	5.08
Browns	64	317	53.91	31.25	24.09	13.07
			2.12	2.28	3.39	3.72
Middle	65	630	46.91	25.95	22.87	10.73
			2.95	2.71	5.07	6.94
Delavan	66	1,487	57.85	33.98	30.45	14.74
			3.49	2.87	4.78	4.03
Como	67	615	59.61	40.60	28.89	15.20
			4.50	4.35	4.43	4.35
Geneva	68	3,684	52.22	28.12	22.14	12.67
			4.11	3.68	4.57	4.71

APPENDIX D5. 14 August 1972 (1022-16373)

Section D5.1. Regression Models, and Correlation Coefficients (Table D5-1)

Twelve Minnesota lakes were extracted from the frame; Maple Lake (241) was not included in the final regression model efforts.

Darling (16)
Le Homme Dieu (18)
Minnewaska (19)
Nest (20)
Green (21)
Wagonga (22)
Clearwater (23)
Maple (241)
Cokato (25)
Buffalo (26)
Silver (28)
Minnetonka (29)

TABLE D5-1. CORRELATIONS BETWEEN GROUND TRUTH AND MSS DATA (COLORS AND COLOR RATIOS) FOR 11 MINNESOTA LAKES IN FRAME 1022-16373 (14 AUGUST 1972).

	PC1	CHLA	LNCHLA	SECCHI	LNSECCHI
GRN	0.422	0.487	0.461	-0.749	-0.734
RED	0.547	0.613	0.610	-0.766	-0.801
IR1	0.890	0.763	0.620	-0.791	-0.920
IR2	0.764	0.758	0.698	-0.626	-0.801
GRNRED	-0.585	-0.646	-0.725	0.415	0.492
GRNIR1	-0.920	-0.704	-0.539	0.557	0.728
GRNIR2	-0.644	-0.602	-0.558	0.268	0.475
REDIR1	-0.940	-0.670	-0.454	0.562	0.728
REDIR2	-0.636	-0.568	-0.495	0.220	0.439
IR1IR2	0.536	0.195	-0.052	-0.597	-0.518

The best regression model for the prediction of trophic state is

$$\widehat{PC1} = 13.150 - 10.626\ GRNIR1 + 2.327\ GRNIR2$$

It explains about 96 percent of the variation about the mean (Table D5-2). The observed and predicted PC1 values are in Table D5-3.

TABLE D5-2. ANALYSIS OF VARIANCE TABLE OF PC1 REGRESSION MODEL FOR 11 MINNESOTA LAKES IN FRAME 1022-16373 (14 AUGUST 1972).

Source	Analysis of Variance			
	df	Sum of Squares	Mean Square	Calculated F
Total (corrected)	10	42.423	4.242	
Regression	2	40.750	20.375	97.488
Residual	8	1.673	0.209	

$R^2 = 0.9606 \times 100 = 96.06\%$ s.e. of estimate = 0.456

TABLE D5-3. PC1 RESIDUALS OF 11 MINNESOTA LAKES IN FRAME 1022-16373 (14 AUGUST 1972).

Lake Name	Serial Number	PC1	$\widehat{PC1}$	$PC1-\widehat{PC1}$
Darling	16	-0.73	-0.34	-0.39
Le Homme Dieu	18	-1.06	-0.84	-0.22
Minnewaska	19	-0.32	-0.68	0.36
Nest	20	0.77	1.04	-0.27
Green	21	-1.10	-1.00	-0.10
Wagonga	22	4.40	4.65	-0.25
Clearwater	23	0.01	0.08	-0.07
Cokato	25	1.61	1.05	0.56
Buffalo	26	2.31	2.92	-0.61
Silver	28	4.79	4.23	0.46
Minnetonka	29	0.73	0.29	0.44

The best model for the prediction of Secchi disc transparency is:

$$\widehat{LNSECCHI} = -4.105 - 154.13\ GRNIR1 + 76.641\ GRNIR2 + 265.290\ REDIR1 - 130.200\ REDIR2$$

It explains about 87 percent of the variation about the mean (Table D5-4). The observed and predicted Secchi disc transparency values are in Table D5-5. Caution is advised in using this model because a relatively large number of variables are incorporated into it.

TABLE D5-4. ANALYSIS OF VARIANCE TABLE OF THE SECCHI DISC TRANSPARENCY REGRESSION MODEL FOR 11 MINNESOTA LAKES IN FRAME 1022-16373 (14 AUGUST 1972).

Source	Analysis of Variance			
	df	Sum of Squares	Mean Square	Calculated F
Total (corrected)	10	9.529	0.953	
Regression	4	8.324	2.081	10.353
Residual	6	1.205	0.201	

R^2 = 0.8735 x 100 = 87.35%   s. e. of estimate - 0.448

TABLE D5-5. SECCHI DISC TRANSPARENCY RESIDUALS OF 11 MINNESOTA LAKES IN FRAME 1022-16373 (14 AUGUST 1972).

Lake Name	Serial Number	SECCHI	$\widehat{\text{SECCHI}}$	SECCHI-$\widehat{\text{SECCHI}}$
Darling	16	2.79	1.87	0.92
Le Homme Dieu	18	1.73	2.45	-0.72
Minnewaska	19	1.55	1.73	-0.18
Nest	20	0.97	0.97	0.00
Green	21	2.29	2.68	-0.39
Wagonga	22	0.23	0.16	0.07
Clearwater	23	1.80	1.25	0.55
Cokato	25	2.74	2.82	-0.08
Buffalo	26	1.98	1.44	0.54
Silver	28	0.15	0.31	-0.16
Minnetonka	29	1.47	1.60	-0.13

Efforts to construct a regression model for the prediction of chlorophyll _a_ drew negative results.

3

Section D5.2. Three-dimensional Color Ratio Model

The color ratio model is displayed in Figure D5-1. Wagonga Lake and Silver Lake are isolated from the other lakes because their IR1 values exceed their RED DN values. The two lakes are often referred to as being hypereutrophic.

Section D5.3. Concatenation of Extracted Lakes

The Frame 1022-16373 concatenation is in Figure D5-2. Portions of Lake Minnetonka and Lake Le Homme Dieu were outside the sensor field of view, resulting in the linear shore line effects. Minnetonka is a complex lake consisting of 15 large bays.

Section D5.4. MSS-Lake Surface Area Relationships

The areal aspects of Frame 1022-16373 are in Table D5-6.

Section D5.5. Lake MSS Descriptive Statistics

The MSS statistics for Frame 1022-16373 are in Table D5-7.

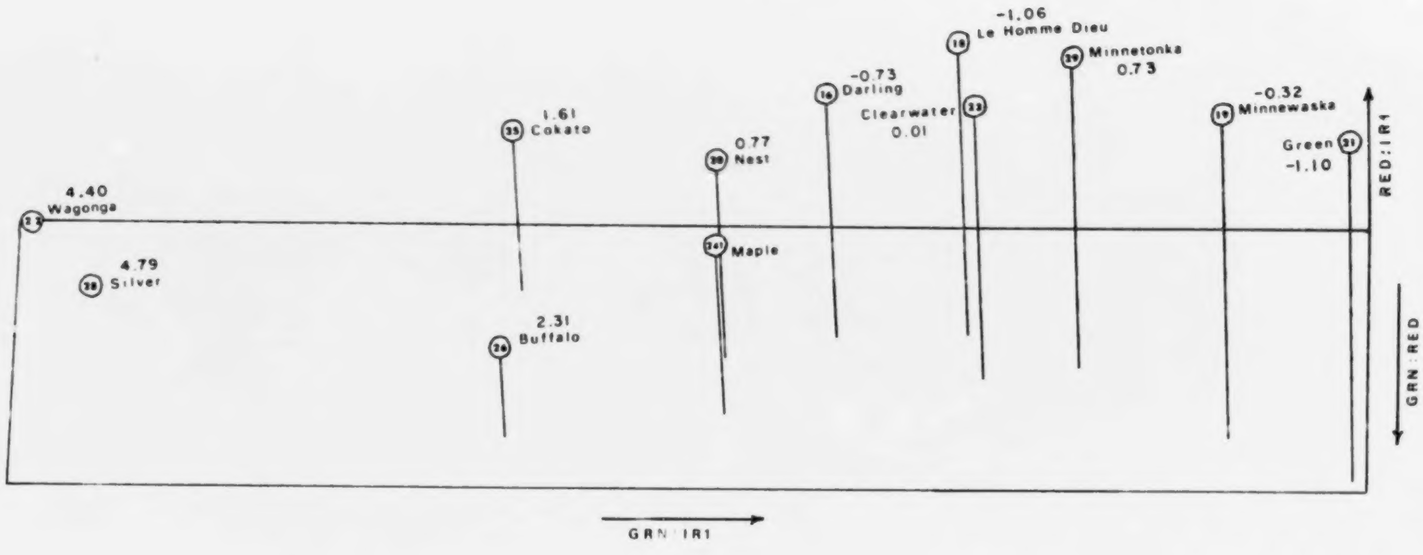


Figure D5-1. Three-dimensional MSS color ratio model of 12 Minnesota lakes extracted from Frame 1022-16373 (14 August 1972).

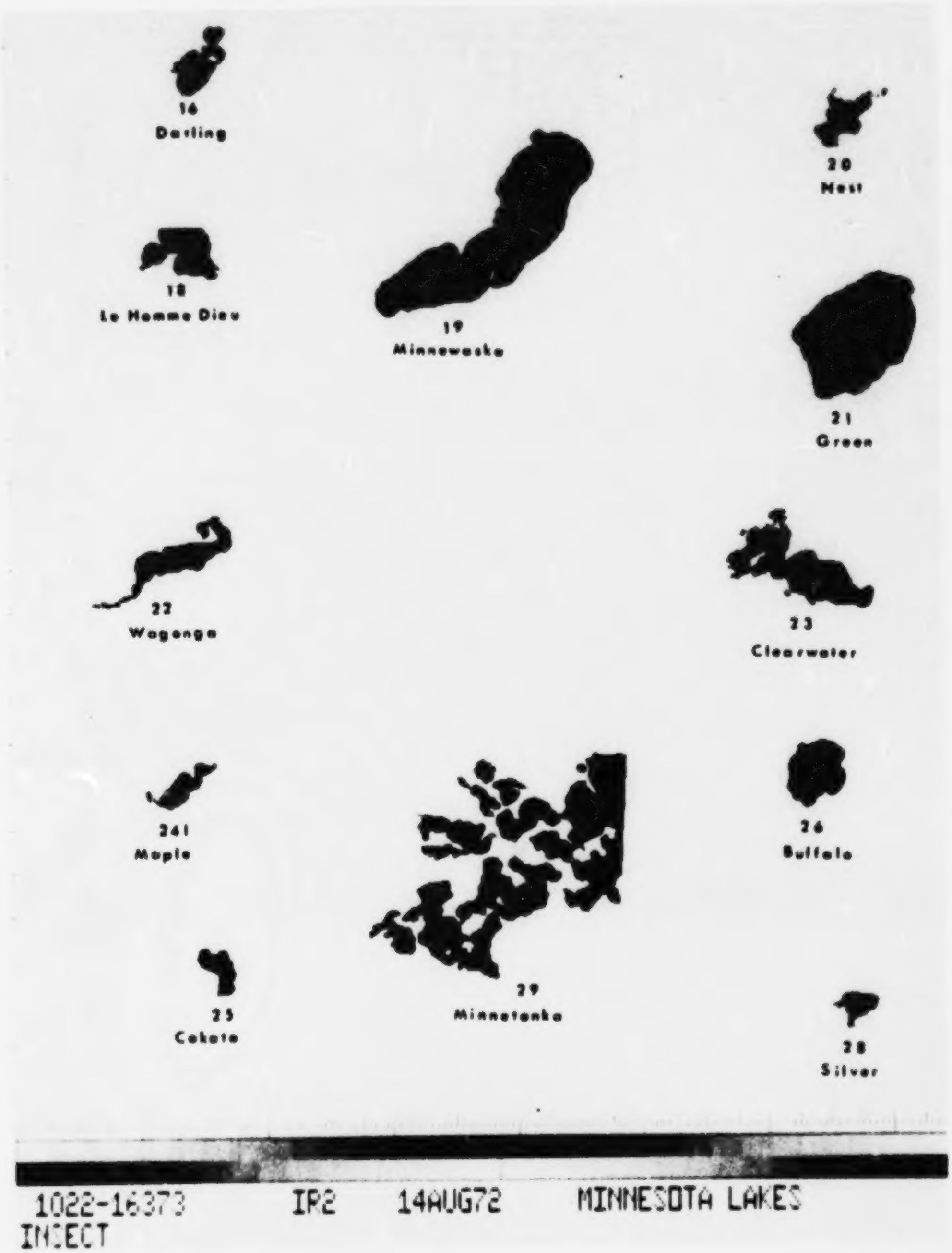

16
Darling
20
Nest
18
Le Homme Dieu
19
Minnewaska
21
Green
22
Wagonga
23
Clearwater
241
Maple
26
Buffalo
25
Cokato
29
Minnetonka
28
Silver
1022-16373 IR2 14AUG72 MINNESOTA LAKES
INJECT

Figure D5-2. IR2 concatenation of 12 Minnesota lakes extracted from Frame 1022-16373 (14 August 1972).

TABLE D5-6. AREAL ASPECTS OF 12 MINNESOTA LAKES EXTRACTED FROM FRAME 1022-16373 (14 AUGUST 1972).

Lake Name	Serial Number	Pixel Count	LANDSAT-1 Lake Area (ha)	Map Lake Area (ha)	Map Area:LANDSAT-1 Area Ratio
Darling	16	824	393.5	386.1	0.981
Le Homme Dieu	18	1,127	538.2	765.7	---[a]
Minnewaska	19	6,996	3,340.9	3,144.5	0.941
Nest	20	778	376.3	382.4	1.016
Green	21	4,846	2,314.2	2,355.8	1.018
Wagonga	22	1,339	639.4	725.2	1.134
Clearwater	23	2,561	1,223.0	1.287.8	1.053
Maple	241	518	247.4	287.3	1.161
Cokato	25	470	224.5	220.2	0.981
Buffalo	26	1,334	637.1	611.1	0.959
Silver	28	367	175.3	170.8	0.974
Minnetonka	29	9,787	4,673.7	5,855.6	---[a]

[a] A portion of the lake was outside the sensor field of view.

TABLE D5-7. MSS DESCRIPTIVE STATISTICS FOR 12 MINNESOTA LAKES EXTRACTED FROM FRAME 1022-16373 (14 AUGUST 1972).

Lake Name	Serial Number	Pixel Count	LANDSAT-1 MSS Bands			
			Green	Red	IR1	IR2
Darling	16	825	49.30[a]	29.37	23.89	13.59
			4.00[b]	4.27	5.28	5.57
Le Homme Dieu	18	1,163	51.76	30.90	24.02	13.51
			3.01	3.33	4.45	5.03
Minnewaska	19	6.996	50.56	28.74	21.66	10.72
			2.65	2.11	3.32	3.97
Nest	20	788	46.81	27.60	23.54	12.08
			2.67	1.98	4.62	5.48
Green	21	4,846	46.25	25.78	19.12	9.31
			2.06	1.59	2.74	3.34
Wagonga	22	1,339	55.77	34.92	36.92	17.18
			3.48	2.96	3.33	3.90
Clearwater	23	2.561	47.64	27.82	22.00	11.15
			2.47	2.09	4.56	5.14
Maple	241	5.8	44.22	25.38	22.23	12.43
			2.16	1.80	4.81	5.26
Cokato	25	470	41.37	25.19	22.37	12.74
			2.87	1.80	4.19	5.39
Buffalo	26	1,334	46.68	26.49	25.36	11.64
			2.28	1.46	4.37	3.88
Silver	28	376	55.75	33.86	35.89	17.10
			2.46	2.30	2.72	4.10
Minnetonka	29	9.787	53.81	31.60	24.11	11.53
			5.30	4.31	4.87	4.85

---

[a] Mean DN value for the lake.
[b] Standard deviation of the lake DN values.

APPENDIX D6. 6 OCTOBER 1973 (1075-16321)

Section D6.1. Regression Models, and Correlation Coefficients (Table D6-1)

Sixteen Minnesota lakes were extracted from the frame. Lakes Sakatah, Calhoun, Zumbro, and Maple were not used in the construction of the regression model.

Clearwater (23
Maple (241)
Cokato (25)
Buffalo (26)
Carrigan (27)
Silver (28)
Minnetonka (29)
Forest (30)
White Bear (31)
St. Croix (32)
Spring (33)
Pepin (34)
Madison (35)
Sakatah (36)
Calhoun (103)
Zumbro (105)

Table D6-1. CORRELATIONS BETWEEN GROUND TRUTH AND MSS DATA (COLOR RATIOS) FOR 12 MINNESOTA LAKES IN FRAME 1075-16321 (6 OCTOBER 1972).

	PC1	CHLA	LNCHLA	SECCHI	LNSECCHI
GRNRED	-0.375	0.067	-0.197	0.582	0.517
GRNIR1	-0.793	-0.391	-0.494	0.706	0.827
GRNIR2	-0.620	-0.425	-0.305	0.424	0.545
REDIR1	-0.663	-0.471	-0.425	0.425	0.606
REDIR2	-0.393	-0.410	-0.173	0.105	0.250
IR1IR2	0.220	-0.146	0.205	-0.349	-0.353

The best model for the prediction of trophic state is:

$$\widehat{PC1} = 11.553 - 7.132 \text{ REDIR } 1$$

This model explains about 44 percent of the variation about the mean (Table D6-2). It is of little practical value. The observed and predicted PC1 values are in Table D6-3.

TABLE D6-2. ANALYSIS OF VARIANCE TABLE FOR THE PC1 REGRESSION MODEL FOR 12 MINNESOTA LAKES EXTRACTED FROM FRAME 1075-16321 (6 OCTOBER 1972).

Source	Analysis of Variance			
	df	Sum of Squares	Mean Square	Calculated F
Total (Corrected)	11	42.274	3.843	
Regression	1	18.561	18.561	7.827
Residual	10	23.713	23.713	

$R^2 = 0.4391 \times 100 = 43.91\%$ s. e. of estimate = 1.540

TABLE D6-3. PC1 RESIDUALS OF 12 MINNESOTA LAKES EXTRACTED FROM FRAME 1075-16321 (6 OCTOBER 1972).

Lake Name	Serial Number	PC1	$\widehat{PC1}$	$PC1-\widehat{PC1}$
Clearwater	23	0.01	0.95	-0.94
Cokato	25	1.61	0.84	0.77
Buffalo	26	2.31	0.14	2.17
Carrigan	27	4.40	3.11	1.29
Silver	28	4.79	4.81	-0.02
Minnetonka	29	0.73	1.06	-0.33
Forest	30	-1.22	0.45	-1.67
White Bear	31	-1.41	1.31	-2.72
St. Croix	32	-0.17	1.40	-1.57
Spring	33	2.33	1.22	1.10
Pepin	34	2.10	0.87	1.23
Madison	35	1.36	0.67	0.69

Section D6.2. Three-dimensional Color Ratio Model

The color ratio model is displayed in Figure D6-1.

Section D6.3. Concatenation of Extracted Lakes

The 15 lakes are displayed in two concatenations, Figure D6-2 and Figure D6-3. A portion of Lake Pepin is outside the sensor field of view, accounting for the linear shoreline. The lake images are in scale and this results in the very small image of Lake Zumbro. Lake St. Croix was truncated during processing.

Section D6.4. MSS-Lake Surface Area Relationships

The areal aspects of the lakes extracted from Frame 1075-16321 are in Table D6-4.

Section D6.5. Lake MSS Descriptive Statistics

The MSS statistics are in Table D6-5.

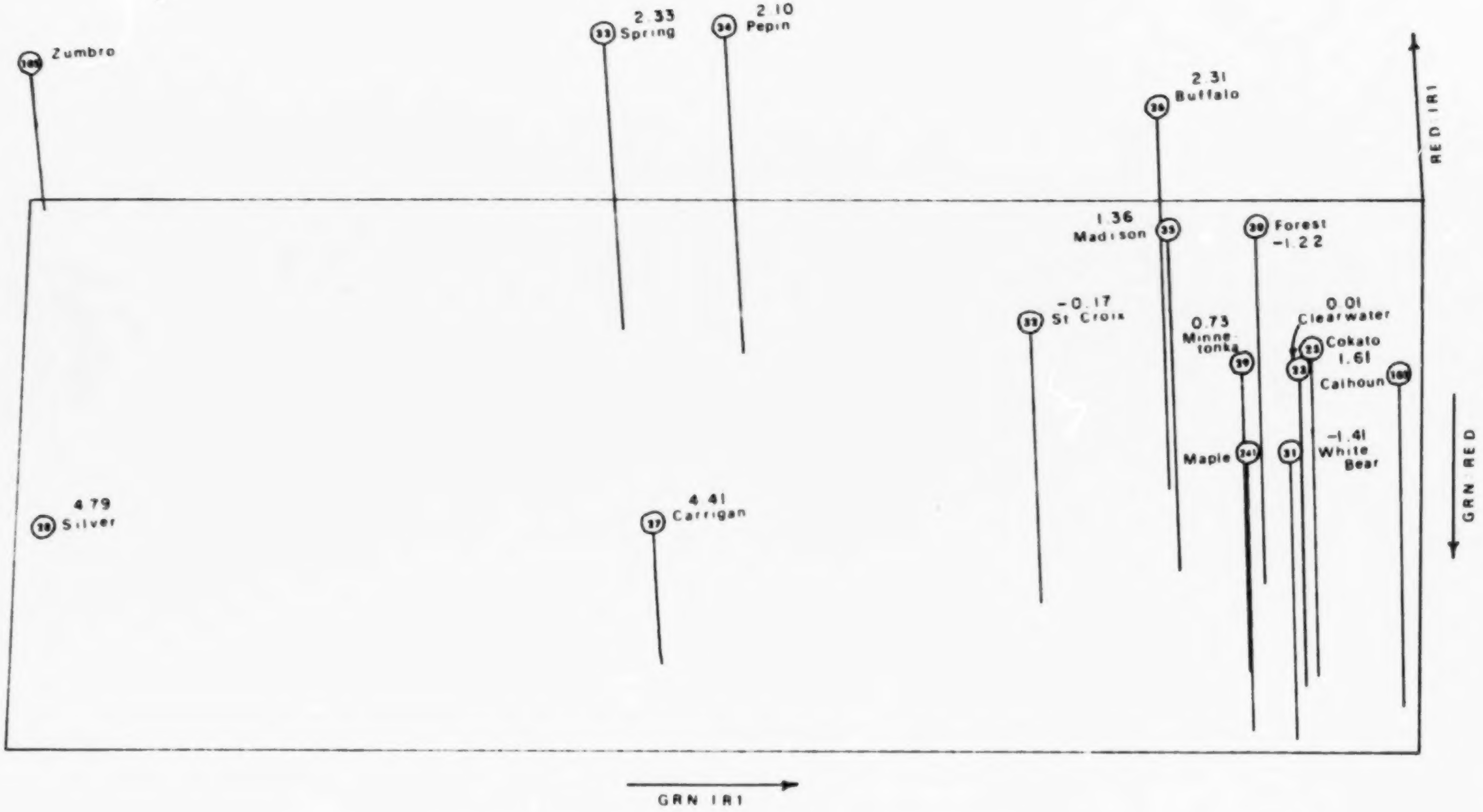


Figure D6-1. Three-dimensional MSS color ratio model of 15 Minnesota lakes extracted from Frame 1075-16321 (6 October 1972).

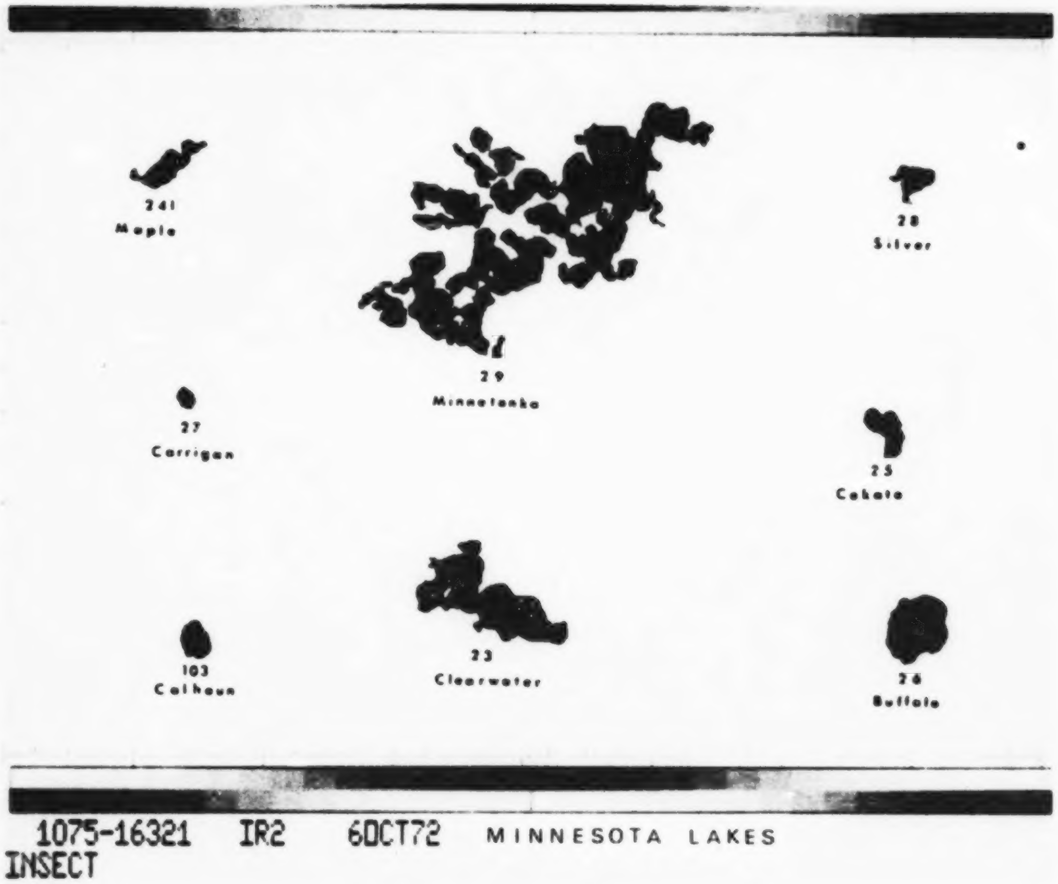

241
Maple
29
Minnetonka
28
Silver
27
Carrigan
25
Cokato
103
Calhoun
23
Clearwater
26
Buffalo
1075-16321 IR2 6OCT72 MINNESOTA LAKES
INSECT

Figure D6-2. IR2 concatenation of 8 Minnesota lakes extracted from Frame 1075-16321 (6 October 1972). Figure D6-3 contains 8 additional lakes extracted from the same frame.

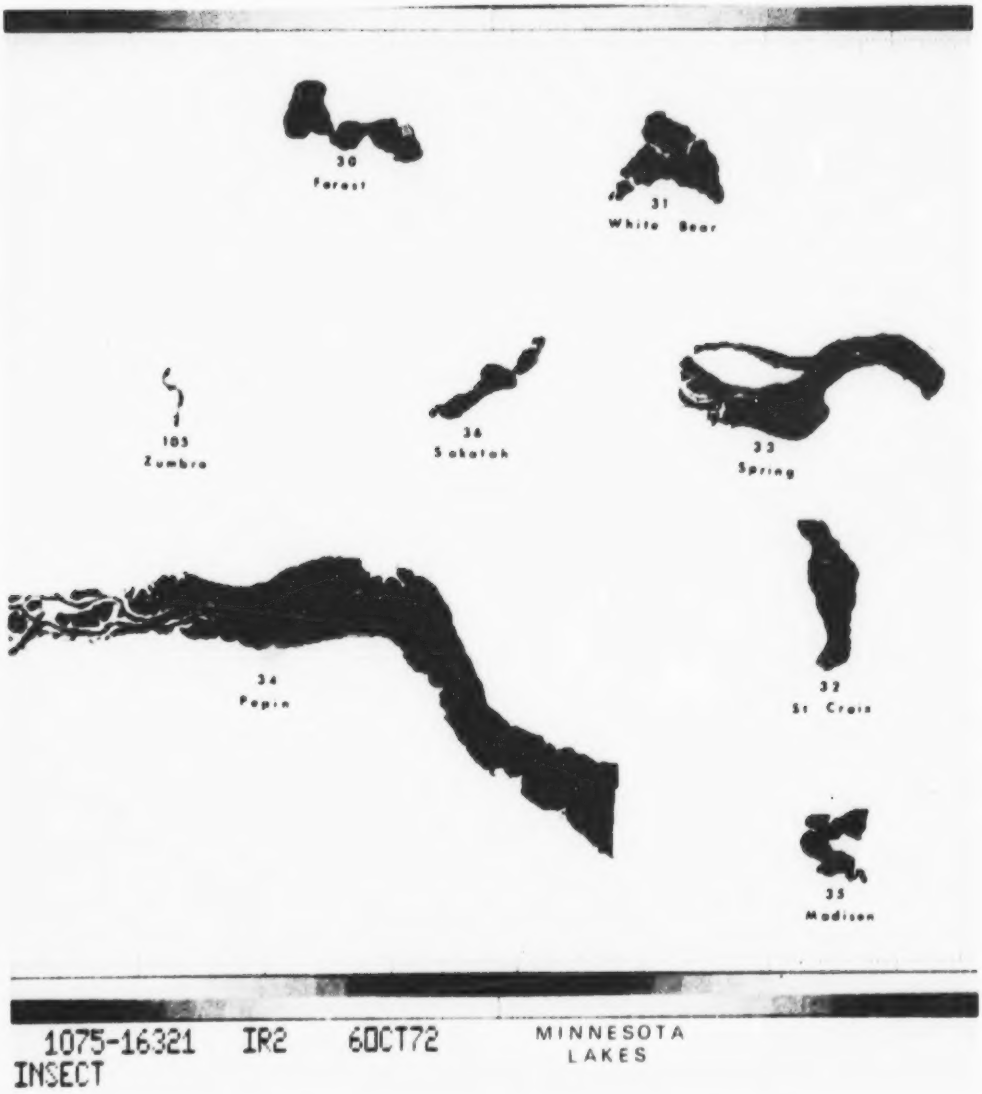

30
Forest
31
White Bear
103
Zumbro
36
Sakatah
33
Spring
34
Pepin
32
St Croix
35
Madison
1075-16321 IR2 6OCT72
MINNESOTA
LAKES
INSECT

Figure D6-3. IR2 concatenation of 8 Minnesota lakes extracted from Frame 1075-16321 (6 October 1972).

TABLE D6-4. AREAL ASPECTS OF 15 MINNESOTA LAKES EXTRACTED FROM FRAME 1075-16321 (6 OCTOBER 1972)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 Lake Area (ha)	Map Lake Area (ha)	Map Area:LANDSAT-1 Area Ratio
Clearwater	23	2,797	1,333.7	1,287.8	0.966
Maple	241	561	268.0	287.3	1.072
Cokato	25	481	229.8	220.2	0.958
Buffalo	26	1,350	644.9	611.1	0.948
Carrigan	27	125	59.7	65.6	1.099
Silver	28	386	184.4	170.8	0.926
Minnetonka	29	12,131	5,795.0	5,855.6	1.011
Forest	30	1,945	929.1	892.8	0.961
White Bear	31	2,233	1,066.7	1,076.5	1.009
St. Croix	32	2,202	1,051.9	3,322.2	-----[a]
Spring	33	5,338	2,550.0	2,391.8	0.938
Pepin	34	16,910	8,077.9	10,117.5	-----[b]
Madison	35	1,224	584.7	541.1	0.925
Calhoun	103	363	173.4	169.6	0.978
Zumbro	105	129	61.6	344.8	-----[c]

[a] The entire image was not extracted from the CCT's.

[b] A portion of the lake was outside the sensor field of view.

[c] The disparity may be related to the long sinuous shape of the water body.

TABLE D6-5. MSS DESCRIPTIVE STATISTICS FOR 15 MINNESOTA LAKES EXTRACTED FROM FRAME 1075-16321 (6 OCTOBER 1972)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 MSS Bands			
			Green	Red	IR1	IR2
Clearwater	23	2,797	33.13[a]	17.03	11.46	5.14
			2.42[b]	2.93	5.70	
Maple	241	561	32.95	16.49	11.59	5.97
			2.42	2.81	6.11	
Cokato	25	481	31.53	16.31	10.86	5.16
			2.90	2.72	5.66	
Buffalo	26	1,350	35.22	20.43	12.77	4.46
			2.16	1.95	4.25	
Carrigan	27	125	32.12	16.71	14.12	7.11
			2.34	2.75	6.40	
Silver	28	386	41.15	23.20	24.56	8.83
			1.61	1.64	2.95	
Minnetonka	29	12,131	35.90	18.61	12.65	5.09
			2.49	2.54	5.23	
Forest	30	1,945	34.35	18.76	12.05	4.99
			2.09	2.39	4.84	
White Bear	31	2,233	33.36	16.63	11.57	5.20
			2.98	3.60	6.25	
St. Croix	32	2,202	31.19	16.84	11.83	5.17
			2.64	3.46	4.98	
Spring	33	5,338	34.64	22.52	15.55	6.60
			2.28	2.47	4.76	
Pepin	34	16,910	33.72	21.56	14.39	5.88
			2.09	2.27	4.40	
Madison	35	1,224	35.37	19.50	12.78	5.67
			2.23	2.35	5.24	
Zumbro	105	129	38.29	27.39	23.05	14.17
			5.44	2.83	5.20	
Calhoun	103	363	33.79	17.15	11.32	4.93
			2.18	3.12	5.28	

[a] Mean DN value for the lake
[b] Standard deviation of the lake DN values.

APPENDIX D7. 8 October 1972 (1077-16431)

Section D7.1. Regression Models, and Correlation Coefficients (Table D7-1)

Ten lakes were extracted from the frame; Lake Winona, Trace Lake, and Big Stone Lake were not used to develop the regression model.

Darling (16)	Minnewaska (19)	Winona (101)
Carlos (17)	Nest (20)	Trace (102)
Le Homme Dieu (18)	Green (21)	Big Stone (104)
	Wagonga (22)	

TABLE D7-1. CORRELATIONS BETWEEN GROUND TRUTH AND MSS DATA (COLOR RATIOS) FOR 7 MINNESOTA LAKES EXTRACTED FROM FRAME 1077-16431 (8 OCTOBER 1972)

	PC1	CHLA	LNCHLA	SECCHI	LNSECCHI
GRNRED	-0.975	-0.936	-0.945	0.876	0.935
GRNIR1	-0.941	-0.962	-0.968	0.738	0.858
GRNIR2	-0.770	-0.786	-0.918	0.474	0.579
REDIR1	-0.918	-0.963	-0.953	0.679	0.826
REDIR2	-0.675	-0.716	-0.864	0.370	0.473
IR1IR2	0.453	0.466	0.168	-0.581	-0.660

The best model for the prediction of trophic state is:

$$\widehat{PC1} = 34.509 - 18.548\ GRNRED$$

This model explains about 95 percent of the variation about the mean (Table D7-2). The observed and predicted PC1 values are in Table D7-3.

TABLE D7-2. ANALYSIS OF VARIANCE TABLE OF THE PC1 REGRESSION FOR 7 MINNESOTA LAKES EXTRACTED FROM FRAME 1077-16431 (8 OCTOBER 1972)

Source	Analysis of Variance			
	df	Sum of Squares	Mean Square	Calculated F
Total (corrected)	6	25.269	4.212	
Regression	1	24.035	24.035	97.433
Residual	5	1,233	0.247	

$R^2 = 0.9512 \times 100 = 95.12\%$ s.e. of estimate = 0.497

TABLE D7-3. PC1 RESIDUALS OF 7 MINNESOTA LAKES EXTRACTED FROM FRAME 1077-16431 (8 OCTOBER 1972)

Lake Name	Serial Number	PC1	$\widehat{PC1}$	PC1-$\widehat{PC1}$
Darling	16	-0.73	-0.92	0.19
Carlos	17	-1.55	-1.18	-0.37
Le Homme Dieu	18	-1.06	-0.68	-0.38
Minnewaska	19	-0.32	-0.06	-0.26
Nest	20	0.77	1.09	-0.32
Green	21	-1.10	-1.90	0.80
Wagonga	22	4.40	4.07	0.33

Section D7.2. Three-dimensional Color Ratio Model

The MSS color ratio model is displayed in Figure D7-1. The PC1 values are in very good agreement with the model.

Section D7.3. Concatenation of Extracted Lakes

The 10 lakes are shown in Figure D7-2.

Section D7.4. MSS-Lake Surface Area Relationships

The areal aspects of the lakes extracted from Frame 1077-16431 are in Table D7-4.

Section D7.5. Lake MSS Descriptive Statistics

The MSS statistics are presented in Table D7-5.

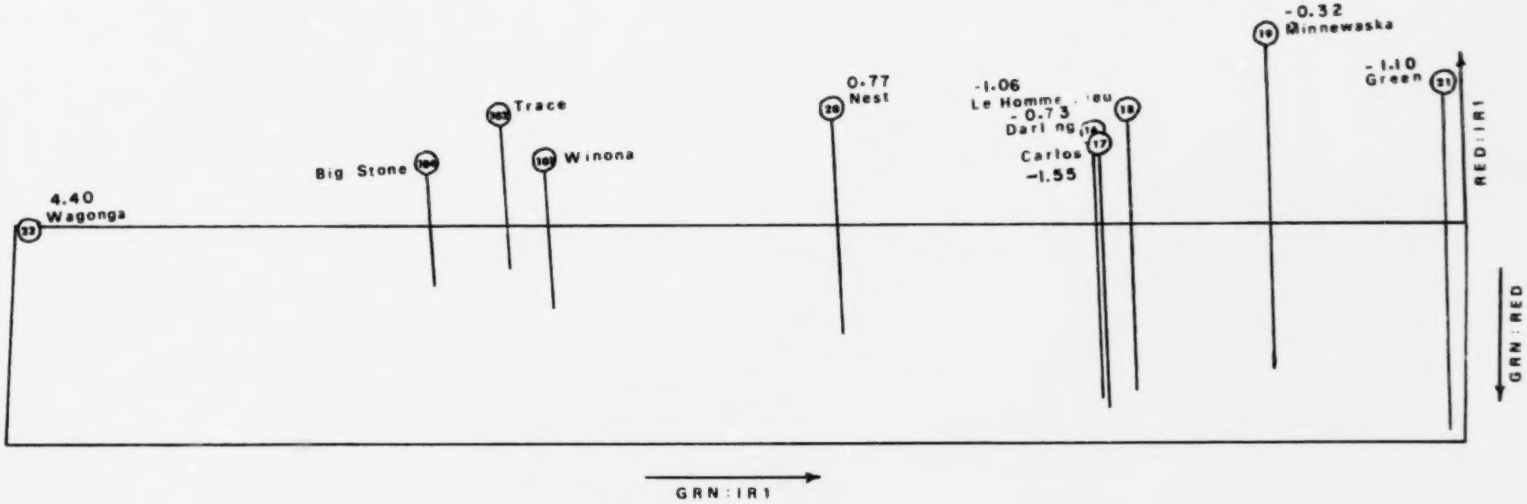


Figure D7-1. Three-dimensional MSS color ratio model of 10 Minnesota lakes extracted from Frame 1077-16431 (8 October 1972).

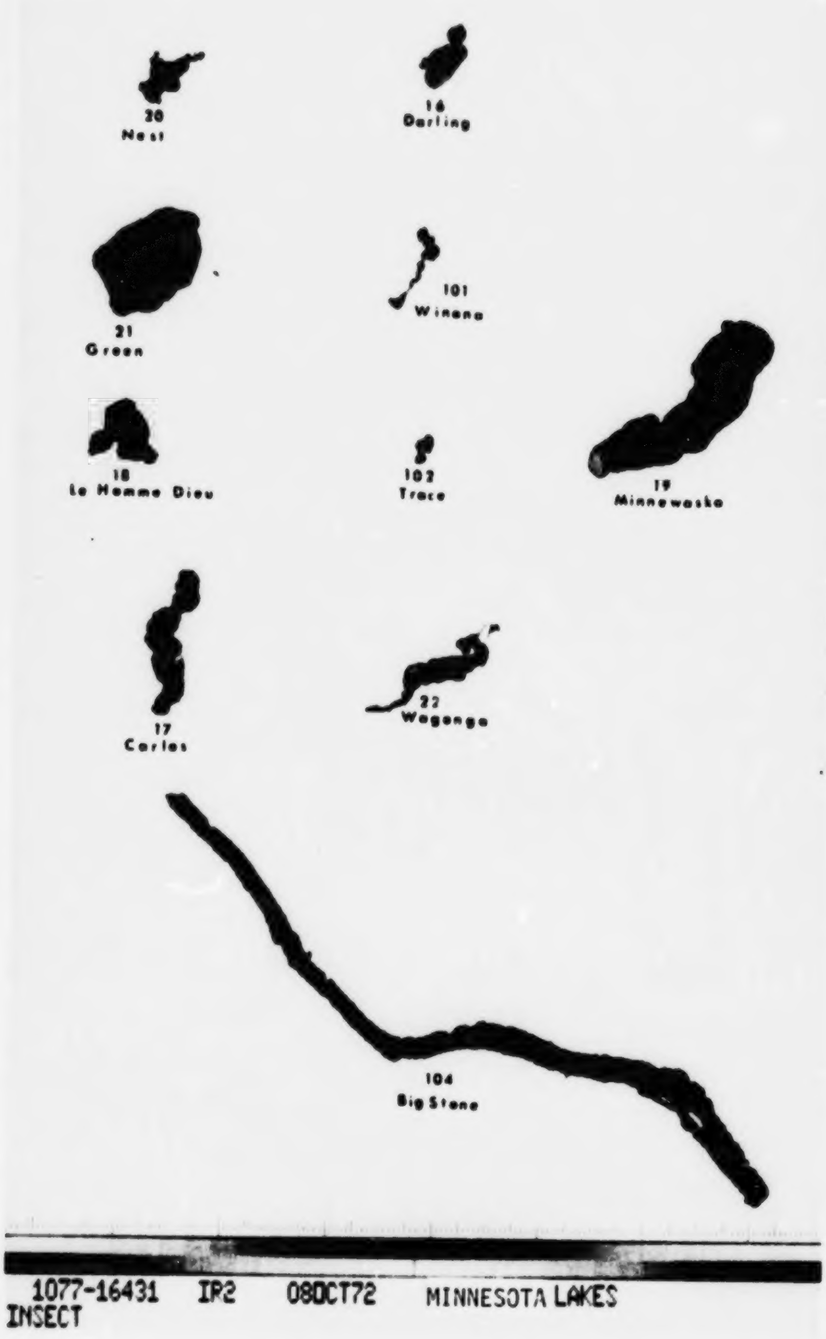

20
Nest
16
Darling
21
Green
101
Winona
18
Le Homme Dieu
102
Trace
19
Minnewaska
17
Carlos
22
Wagonga
104
Big Stone
1077-16431 IR2 08OCT72 MINNESOTA LAKES
INSECT

Figure D7-2. IR2 concatenation of 10 Minnesota lakes extracted from Frame 1077-16431 (8 October 1972).

TABLE D7-4. AREAL ASPECTS OF 10 MINNESOTA LAKES EXTRACTED FROM FRAME 1077-16431 (8 OCTOBER 1972)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 Lake Area (ha)	Map Lake Area (ha)	Map Area:LANDSAT-1 Area Ratio
Carlos	17	2,200	1,050.9	1,019.8	0.970
Le Homme Dieu	18	1,561	745.7	705.8	0.947
Darling	16	923	440.9	386.1	0.876
Minnewaska	19	7,028	3,357.3	2,877.4	0.857
Nest	20	872	416.6	382.4	0.918
Green	21	4,986	2,381.8	2,187.8	0.919
Wagonga	22	1,501	717.0	654.4	0.913
Winona	101	425	203.0	73.3	-----[a]
Trace	102	102	89.8		
Big Stone	104	10,407	4,971.4	5,103.3	1.027

[a] The LANDSAT-1 image includes pixels from Lake Agnes and Lake Henry.

TABLE D7-5. MSS DESCRIPTIVE STATISTICS FOR 10 MINNESOTA LAKES EXTRACTED FROM FRAME 1077-16431 (8 OCTOBER 1972)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 MSS Bands			
			Green	Red	IR1	IR2
Carlos	17	2,200	33.19[a]	17.25	10.58	4.74
			2.86[b]	3.36	4.56	
Le Homme Dieu	18	1,561	33.27	17.54	10.48	4.50
			2.56	2.95	4.16	
Darling	16	923	31.72	16.61	10.14	4.64
			1.91	2.76	4.29	
Minnewaska	19	7,028	37.48	20.11	11.14	4.173
			1.68	2.07	3.05	3.46
Nest	20	872	31.94	17.73	11.53	5.79
			1.95	2.26	4.87	
Green	21	4,986	33.69	17.16	9.35	3.87
			2.27	2.12	2.81	3.20
Wagonga	22	1,501	40.97	24.96	24.91	9.28
			2.47	2.11	3.20	4.96
Trace	102	188	36.20	21.38	15.68	9.49
			4.62	5.21	7.02	8.05
Winona	101	425	35.02	19.92	14.76	7.57
			2.40	3.09	6.02	6.91
Big Stone	104	10,407	38.76	22.56	17.58	6.11
			1.93	3.05	3.78	4.50

[a] Mean DN value for the lake.
[b] Standard deviation of the lake DN values.

APPENDIX D8. 28 MAY 1973 (1309-16325)

Section D8.1. Regression Models, and Correlation Coefficients (Table D8-1)

Thirteen Minnesota lakes were extracted from the frame. Lakes Calhoun and Maple were not used in the development of the regression model.

Clearwater (23)
Maple (24)
Cokato (25)
Buffalo (26)
Carrigan (27)
Silver (28)
Forest (30)
White Bear (31)
St. Croix (32)
Spring (33)
Madison (35)
Sakatah (36)
Calhoun (103)

TABLE D8-1. CORRELATIONS BETWEEN MSS DATA (COLORS AND COLOR RATIOS) AND PC1 VALUES FOR 11 MINNESOTA LAKES EXTRACTED FROM FRAME 1309-16325 (28 MAY 1973)

	PC1
GRN	-0.068
RED	-0.040
IR1	-0.014
IR2	-0.259
GRNRED	0.061
GRNIR1	0.017
GRNIR2	0.316
REDIR1	-0.036
REDIR2	0.434
IR1IR2	0.702

The best model for the prediction of trophic state is:

$$\widehat{PC1} = -16.537 + 9.844 \text{ IR1IR2}$$

This model explains about 49 percent of the variation about the mean (Table D8-2) and is not adequate. The observed and predicted PC1 values are in Table D8-3.

TABLE D8-2. ANALYSIS OF VARIANCE TABLE OF THE PC1 REGRESSION MODEL FOR 11 MINNESOTA LAKES EXTRACTED FROM FRAME 1309-16325 (28 MAY 1973)

Source	Analysis of Variance			
	df	Sum of Squares	Mean Square	Calculated F
Total (corrected)	10	41.326	4.133	
Regression	1	20.385	20.385	8.761
Residual	9	20.941	2.327	

R^2 = 0.4933 x 100 = 49.33% s.e. of estimate = 1.525

TABLE D8-3. PC1 RESIDUALS OF 11 MINNESOTA LAKE EXTRACTED FROM FRAME 1309-16325 (28 MAY 1973)

Lake Name	Serial Number	PC1	$\widehat{PC1}$	PC1-$\widehat{PC1}$
Clearwater	23	0.01	2.88	-2.87
Cokato	25	1.61	2.07	-0.46
Buffalo	26	2.31	2.29	0.02
Carrigan	27	4.40	1.78	2.62
Silver	28	4.78	3.89	0.89
Forest	30	-1.22	-0.19	-1.03
White Bear	31	-1.41	-0.04	-1.34
St. Croix	32	-0.17	-0.82	0.65
Spring	33	2.33	1.65	0.68
Madison	35	1.36	1.51	-0.15
Sakatah	36	1.38	0.38	1.00

Section D8.2. Three-dimensional Color Ratio Model

The MSS color ratio model is displayed in Figure D8-1. There appears to be little agreement between lake position in the model and trophic state as defined by the PC1 value.

Section D8.3. Concatenation of Extracted Lakes

The concatenation of 13 lakes is displayed as Figure D8-2. Sakatah Lake includes both Upper Sakatah Lake and Lower Sakatah Lake.

Section D8.4. MSS-Lake Surface Area Relationships

The areal aspects of the lakes are in Table D8-5.

Section D8.5. Lake MSS Descriptive Statistics

The MSS statistics are in Table D8-4.

TABLE D8-4. DESCRIPTIVE STATISTICS FOR 13 MINNESOTA LAKES EXTRACTED FROM FRAME 1309-16325 (28 MAY 1973)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 MSS Bands			
			Green	Red	IR1	IR2
Clearwater	23	2,689	45.89[a]	26.74	19.09	9.68
			3.24[b]	2.94	3.92	4.18
Maple	24	584	49.09	28.11	21.15	11.19
			3.04	2.48	4.40	4.91
Cokato	25	442	44.73	26.60	20.32	10.75
			2.47	2.08	3.51	4.05
Buffalo	26	1,327	51.01	31.60	22.04	11.52
			2.06	2.17	2.82	3.24
Carrigan	27	401	48.12	28.29	20.86	11.21
			2.37	2.12	3.49	4.26
Silver	28	368	51.79	31.92	28.36	13.67
			1.71	1.58	3.04	3.80
Forest	30	1,871	52.71	33.06	26.18	15.76
			6.32	2.59	3.04	3.31
White Bear	31	2,093	53.58	32.92	26.85	16.02
			2.31	2.80	3.47	3.15
St. Croix	32	2,133	53.50	37.24	30.31	18.98
			2.11	2.62	2.76	2.77
Spring	33	4,856	61.44	47.49	37.79	20.46
			2.89	3.61	2.91	3.01
Madison	35	1,177	50.78	31.15	22.67	12.36
			2.10	2.19	3.33	3.89
Sakatah	36	977	53.09	35.79	27.31	15.90
			2.16	2.98	3.27	3.78
Calhoun	103	339	51.72	30.17	23.93	13.81
			1.95	2.21	2.89	3.32

[a] Mean DN value for the lake.
[b] Standard deviation of the lake DN values.

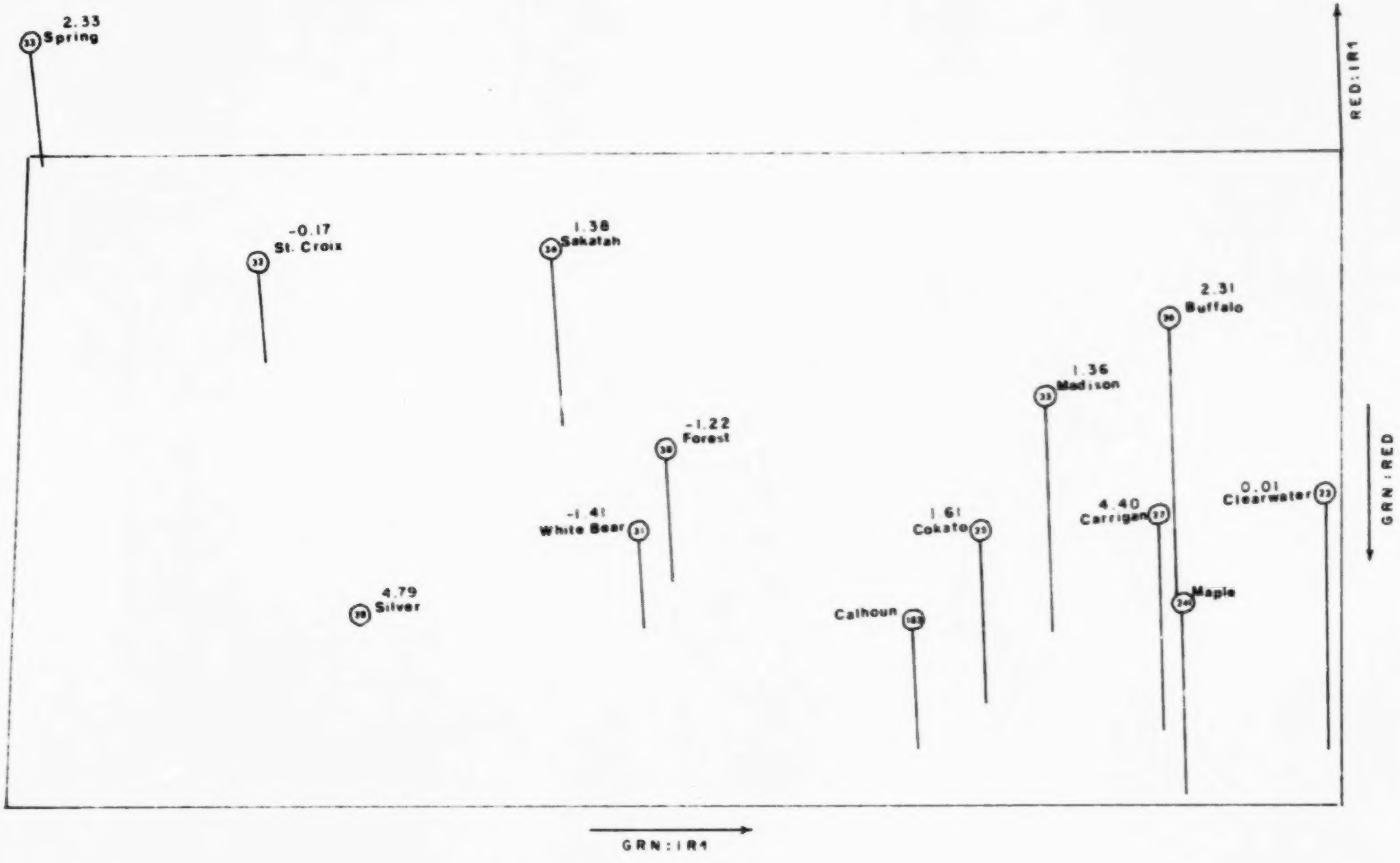


Figure D8-1. Three-dimensional MSS color ratio model of 13 Minnesota lakes extracted from Frame 1309-16325 (28 May 1973).

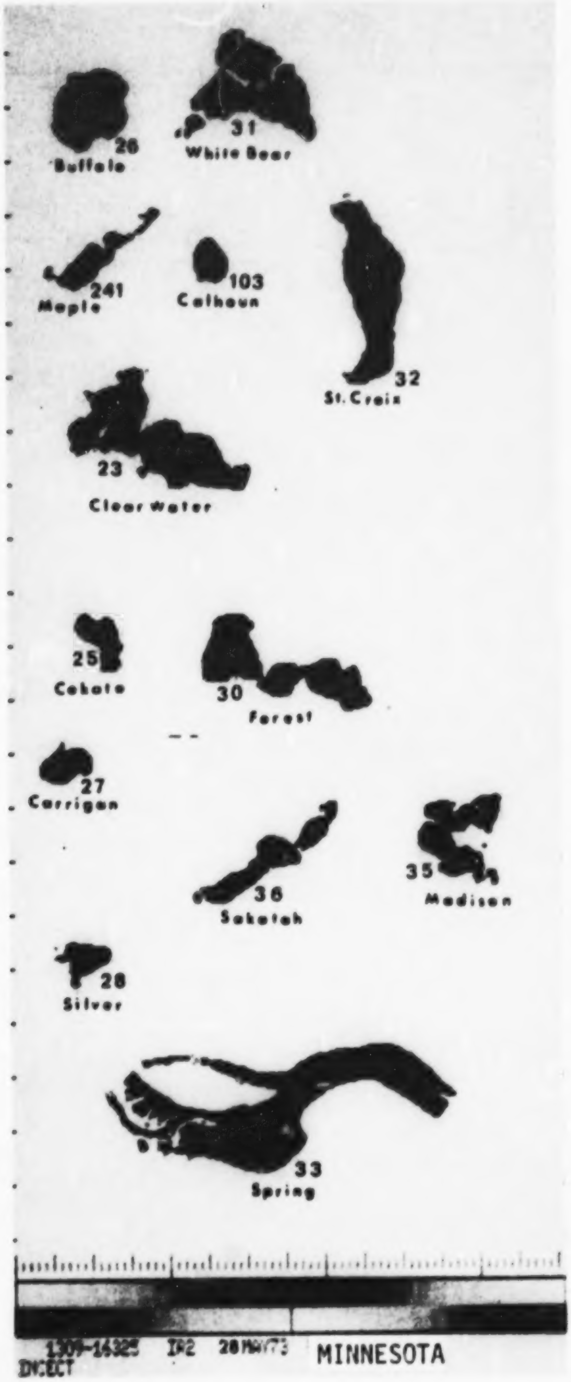

26
Buffalo
31
White Bear
241
Maple
103
Calhoun
32
St. Croix
23
Clear Water
25
Cokato
30
Forest
27
Carrigan
36
Sakatah
35
Madison
28
Silver
33
Spring
1309-16325 IR2 28MAY73
MINNESOTA

Figure D8-2. IR2 concatenation of 13 Minnesota lakes extracted from Frame 1309-16325 (28 May 1973).

TABLE D8-5. AREAL ASPECTS OF 13 MINNESOTA LAKES EXTRACTED FROM FRAME 1309-16325 (28 MAY 1973)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 Lake Area (ha)	Map Lake Area (ha)	Map Area:LANDSAT-1 Area Ratio
Clearwater	23	2,689	1,284.5	1,287.8	1.003
Maple	241	584	279.0	287.3	1.030
Cokato	25	442	211.1	220.2	1.043
Buffalo	26	1,327	633.0	611.1	0.965
Carrigan	27	401	191.6	65.0	-----[a]
Silver	28	368	175.8	170.8	0.972
Forest	30	1,871	893.8	892.8	0.999
White Bear	31	2,093	999.8	1,076.5	1.077
St. Croix	32	2,133	1,018.9	3,322.2	-----[b]
Spring	33	4,856	2,319.7	2,391.8	1.031
Madison	35	1,177	562.3	541.1	0.962
Sakatah	36	977	466.7	497.0	1.065
Calhoun	103	339	161.9	169.6	1.048

[a] A portion of the lake was outside the sensor field of view.
[b] The entire lake image was not extracted from the CCT's.

APPENDIX D9. 3 July 1973 (1345-16322)

Section D9.1. Regression Models, and Correlation Coefficients (Table D9-1)

Fourteen Minnesota lakes were extracted from the frame. Lakes Calhoun and Maple were not used in developing the regression model.

Clearwater (23)
Maple (241)
Cokato (25)
Buffalo (26)
Carrigan (27)
Silver (28)
Minnetonka (29)
Forest (30)
White Bear (31)
St. Croix (32)
Spring (33)
Madison (35)
Sakatah (36)
Calhoun (103)

TABLE D9-1. CORRELATIONS BETWEEN MSS DATA (COLOR RATIOS) AND PC1 VALUES FOR 12 MINNESOTA LAKES EXTRACTED FROM FRAME 1345-16322 (3 JULY 1973)

	PC1
GRNRED	0.239
GRNIR1	-0.788
GRNIR2	-0.641
REDIR1	-0.837
REDIR2	-0.642
IR1IR2	0.172

The best model for the prediction of trophic state is:

$$\widehat{PC1} = 10.544 - 7.240 \text{ REDIR1}$$

This model explains about 70 percent of the variation about the mean (Table D9-2), but is of little practical value. The observed and predicted PC1 values are in Table D9-3.

TABLE D9-2. ANALYSIS OF VARIANCE TABLE OF THE PC1 REGRESSION MODEL FOR 12 MINNESOTA LAKES EXTRACTED FROM FRAME 1345-16322 (3 JULY 1973)

Source	Analysis of Variance			
	df	Sum of Squares	Mean Square	Calculated F
Total (corrected)	11	41.744	3.795	
Regression	1	29.260	29.260	23.438
Residual	10	12.484	1.248	

$R^2 = 0.7009 \times 100 = 70.09\%$ s.e. of estimate = 1.117

TABLE D9-3. PC1 RESIDUALS OF 12 MINNESOTA LAKES EXTRACTED FROM FRAME 1345-16322 (3 JULY 1973)

Lake Name	Serial Number	PC1	$\widehat{PC1}$	$PC1-\widehat{PC1}$
Clearwater	23	0.01	-0.08	0.09
Cokato	25	1.61	0.33	1.28
Buffalo	26	2.31	3.05	-0.74
Carrigan	27	4.40	3.13	1.27
Silver	28	4.79	4.90	-0.11
Minnetonka	29	0.73	-0.31	1.04
Forest	30	-1.22	-0.54	-0.68
White Bear	31	-1.40	0.75	-2.15
St. Croix	32	-0.17	0.76	-0.93
Spring	33	2.33	1.25	1.08
Madison	35	1.36	0.98	0.38
Sakatah	36	1.38	1.92	-0.54

Section D9.2. Three-dimensional Color Ratio Model

The MSS color ratio model is displayed in Figure D9-1. Silver Lake's IR1 DN level exceeds its RED DN level; this isolates it from the other lakes.

Section D9.3. Concatenation of Extracted Lakes

The concatenation of the 14 lakes is in Figure D9-2.

Section D9.4. MSS-Lake Surface Area Relationships

The areal aspects of the 14 lakes are in Table D9-5.

Section D9.5. Lake MSS Descriptive Statistics

The MSS statistics are in Table D9-4.

TABLE D9-4. MSS DESCRIPTIVE STATISTICS FOR 14 MINNESOTA LAKES EXTRACTED FROM FRAME 1345-16322 (3 JULY 1973)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 MSS Bands			
			Green	Red	IR1	IR2
Clearwater	23	2,485	47.29[a]	26.59	18.11	7.21
			3.25[b]	2.49	9.85	5.19
Maple	241	505	43.43	24.15	16.94	7.86
			2.49	2.21	7.55	5.43
Cokato	25	437	41.50	22.54	15.98	6.88
			2.45	2.27	3.67	4.42
Buffalo	26	1,285	47.77	26.01	25.12	9.04
			2.01	1.63	4.68	3.72
Carrigan	27	106	47.41	25.16	24.56	13.35
			2.04	1.37	4.44	3.92
Silver	28	346	50.44	27.61	35.42	13.43
			1.68	1.25	3.30	3.94
Minnetonka	29	11,239	47.05	25.44	16.96	6.89
			3.79	3.26	9.07	4.66
Forest	30	1,818	42.24	24.61	16.07	7.82
			2.27	2.24	3.99	4.22
White Bear	31	2,094	40.94	22.78	16.84	7.94
			3.05	3.27	8.33	4.41
St. Croix	32	2,145	38.78	22.50	16.66	6.59
			2.26	2.77	7.24	4.26
Spring	33	4,945	43.93	28.36	22.09	8.03
			2.51	2.27	1.68	4.55
Madison	35	1,151	46.84	27.10	20.51	7.79
			2.23	1.70	8.51	4.63
Sakatah	36	986	44.46	26.43	22.18	9.22
			2.25	1.87	4.13	4.40
Calhoun	103	342	50.45	24.91	15.65	6.29
			2.22	2.57	3.75	4.13

[a] Mean DN value for the lake.
[b] Standard deviation of the lake DN values.

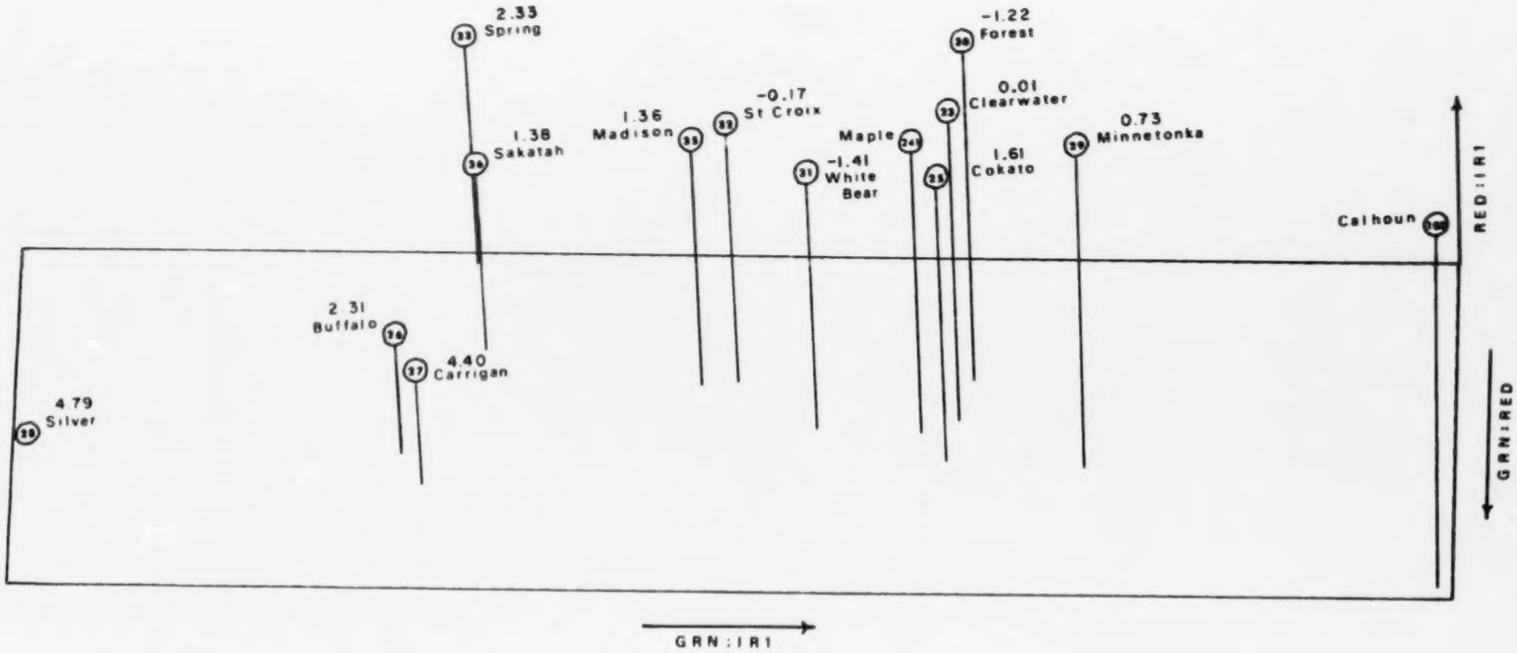


Figure D9-1. Three-dimensional MSS color ratio model of 14 Minnesota lakes extracted from Frame 1345-16322 (3 July 1973).

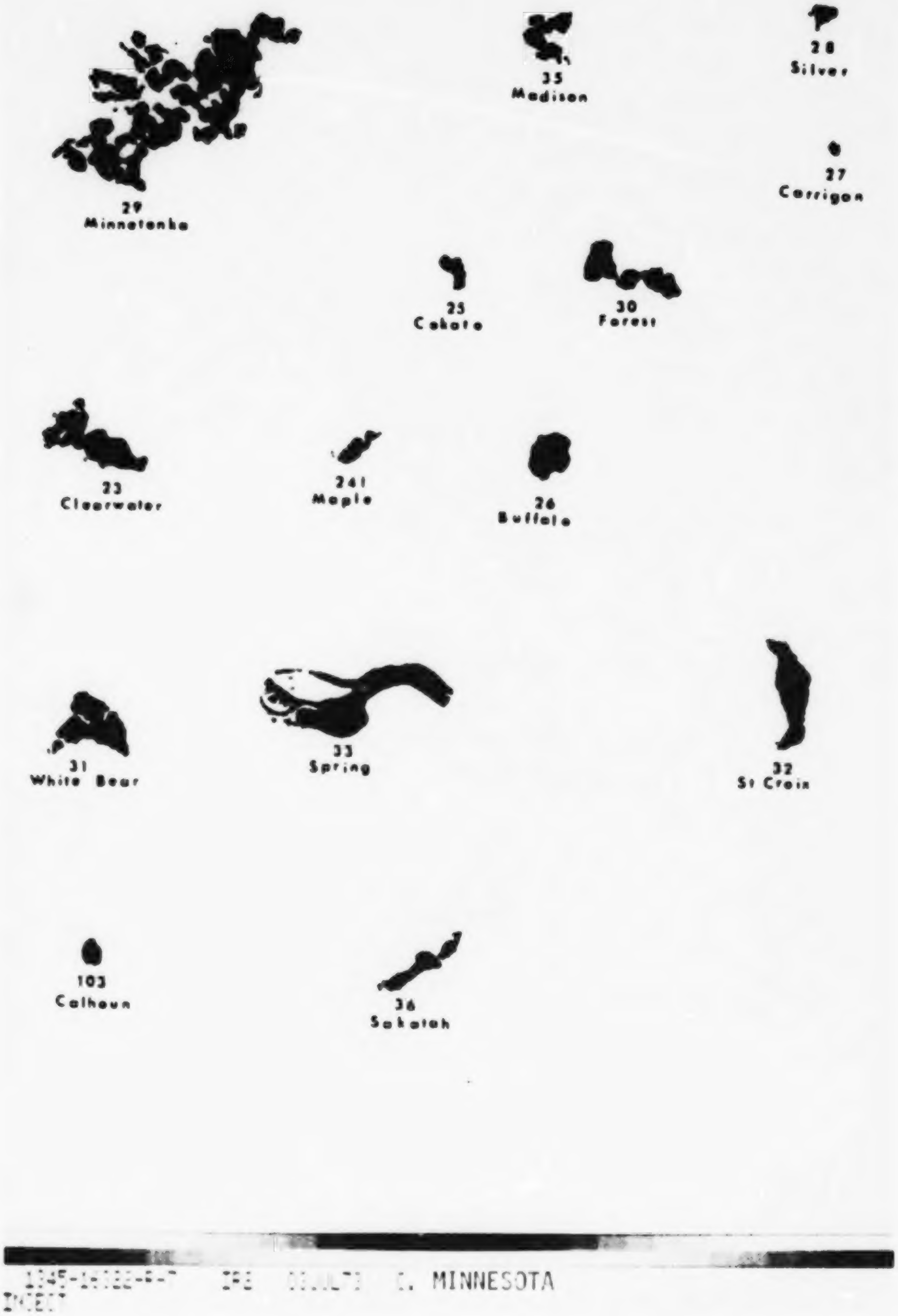

29
Minnetonka
35
Madison
28
Silver
27
Carrigan
25
Cokato
30
Forest
23
Clearwater
241
Maple
26
Buffalo
31
White Bear
33
Spring
32
St Croix
103
Calhoun
36
Sakatah
1345-16322-6-7 IR2 03JUL73 C. MINNESOTA

Figure D9-2. IR2 concatenation of 14 Minnesota lakes extracted from Frame 1345-16322 (3 July 1973).

TABLE D9-5. AREAL ASPECTS OF 14 MINNESOTA LAKES EXTRACTED FROM FRAME 1345-16322 (3 JULY 1973)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 Lake Area (ha)	Map Lake Area (ha)	Map Area:LANDSAT-1 Area Ratio
Clearwater	23	2,485	1,187.1	1,287.8	1.085
Maple	241	505	241.2	287.3	1.191
Cokato	25	437	208.8	220.2	1.055
Buffalo	26	1,285	613.8	611.1	0.996
Carrigan	27	106	50.6	65.6	1.296
Silver	28	346	165.3	170.8	1.033
Minnetonka	29	11,239	5,368.9	5,855.6	1.091
Forest	30	1,818	868.5	892.8	1.028
White Bear	31	2,094	1,000.3	1,076.5	1.076
St. Croix	32	2,145	1,024.7	3,322.2	-----[a]
Spring	33	4,945	2,362.2	2,391.8	1,013
Madison	35	1,151	549.8	541.1	0.984
Sakatah	36	986	471.0	497.0	1.055
Calhoun	103	342	163.4	169.6	1.038

[a] The entire lake image was not extracted from the CCT's.

APPENDIX D10. 4 July 1973 (1346-16381)

Section D10.1. Regression Models, and Correlation Coefficients (Table D10-1)

Eight Minnesota lakes were extracted from the frame; Cottonwood Lake was not used in developing the regression model.

Nest (20)
Green (21)
Wagonga (22)
Cokato (25)
Buffalo (26)
Carrigan (27)
Silver (28)
Cottonwood (111)

TABLE D10-1. CORRELATIONS BETWEEN MSS DATA (COLORS AND COLOR RATIOS) AND PC1 VALUES FOR 7 MINNESOTA LAKES EXTRACTED FROM FRAME 1346-16381 (4 JULY 1973)

	PC1
GRN	0.874
RED	0.829
IR1	0.903
IR2	0.829
GRNRED	-0.595
GRNIR1	-0.956
GRNIR2	-0.800
REDIR1	-0.961
REDIR2	-0.839
IR1IR2	0.573

The best model for the prediction of lake trophic state is:

$$\widehat{PC1} = 11.715 - 8.277\ \mathrm{REDIR1}$$

This model accounts for about 92 percent of the variation about the mean (Table D10-2). The observed and predicted PC1 values are in Table D10-3.

TABLE D10-2. ANALYSIS OF VARIANCE TABLE OF THE PC1 REGRESSION MODEL FOR 7 MINNESOTA LAKES EXTRACTED FROM FRAME 1346-16381 (4 JULY 1973)

Source	Analysis of Variance			
	df	Sum of Squares	Mean Square	Calculated F
Total (corrected)	6	29.233	4.872	
Regression	1	26.994	26.994	60.255
Residual	5	2.238	0.448	

R^2 = 0.9234 x 100 = 92.34%   s.e. of estimate = 0.669

TABLE D10-3. PC1 RESIDUALS OF 7 MINNESOTA LAKES EXTRACTED FROM FRAME 1346-16381 (4 JULY 1973)

Lake Name	Serial Number	PC1	$\widehat{PC1}$	PC1-$\widehat{PC1}$
Nest	20	0.77	0.33	0.44
Green	21	-1.10	-0.34	-0.76
Wagonga	22	4.40	4.04	0.36
Cokato	25	1.61	0.86	0.75
Buffalo	26	2.31	3.07	-0.76
Carrigan	27	4.40	4.71	-0.31
Silver	28	4.79	4.49	0.30

Section D10.2. Three-dimensional Color Ratio Model

The MSS color ratio model is displayed in Figure D10-1. Lakes Wagonga, Carrigan, and Silver have IR1 values which exceed their RED DN values.

Section 10.3. Concatentation of Extracted Lakes

The concatenation of eight lakes is in Figure D10-2.

Section 10.4. MSS-Lake Surface Area Relationships

The areal aspects of the eight lakes are in Table D10-4.

Section D10.5. Lake MSS Descriptive Statistics

The MSS statistics are in Table D10-5.

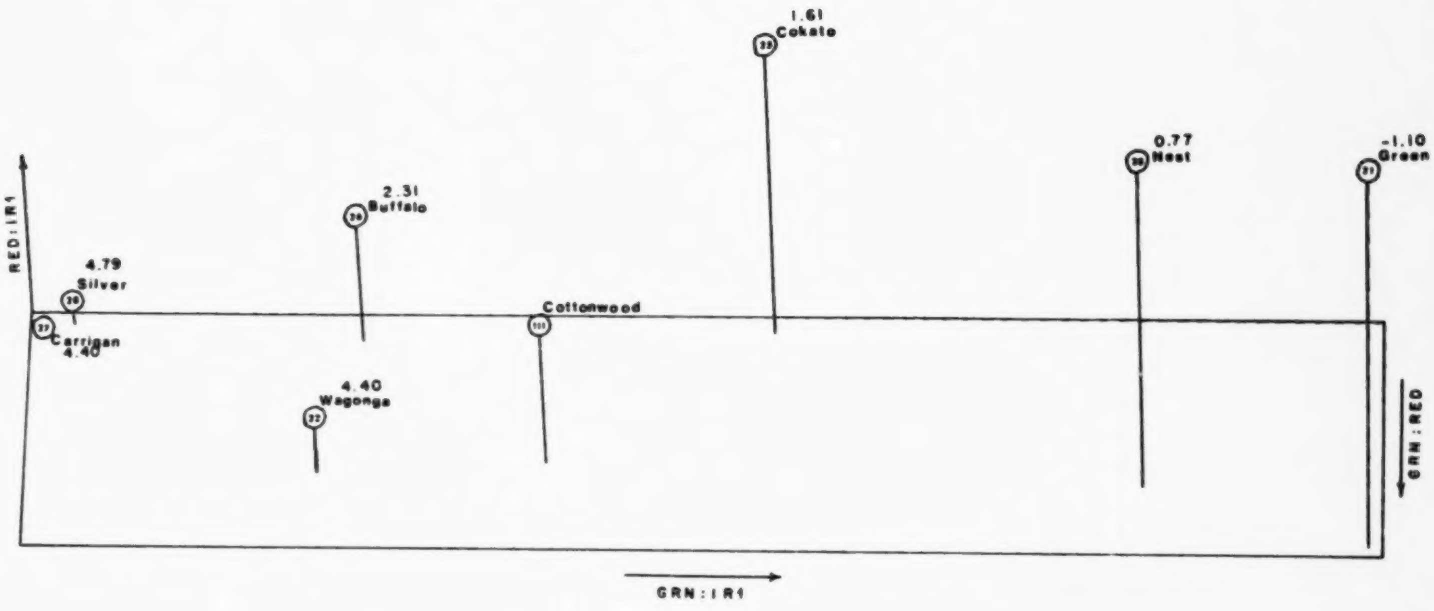


Figure D10-1. Three-dimensional MSS color ratio model of 8 Minnesota lakes extracted from Frame 1346-16381 (4 July 1973).

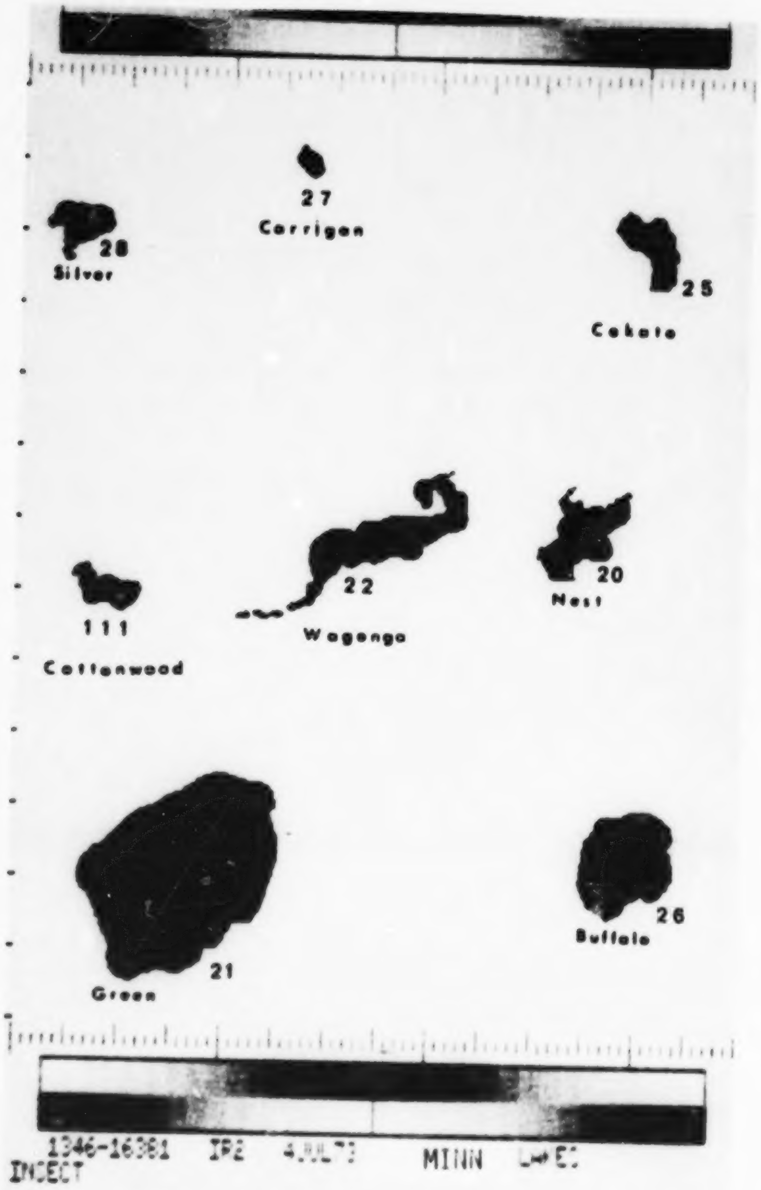

27
Corrigan
28
Silver
25
Cokato
20
Nest
22
Wagenga
111
Cottonwood
26
Buffalo
21
Green
1346-16381
IR2
4JUL73
MINN
LAKES
INJECT

Figure D10-2. IR2 concatenation of 8 Minnesota lakes extracted from Frame 1346-16381 (4 July 1973).

TABLE D10-4. AREAL ASPECTS OF 8 MINNESOTA LAKES EXTRACTED FROM FRAME 1346-16381 (4 JULY 1973)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 Lake Area (ha)	Map Lake Area (ha)	Map Area:LANDSAT-1 Area Ratio
Nest	20	724	345.9	382.4	1.106
Green	21	4,701	2,245.7	2,187.8	0.974
Wagonga	22	1,275	609.1	654.4	1.074
Cokato	25	434	207.3	220.2	1.062
Buffalo	26	1,300	721.0	611.1	0.984
Carrigan	27	98	46.8	75.6	1.402
Silver	28	346	165.3	170.8	1.033
Cottonwood	111	293	140.0	149.7	1.069

TABLE D10-5. MSS DESCRIPTIVE STATISTICS FOR 8 MINNESOTA LAKES EXTRACTED FROM FRAME 1346-16381 (4 JULY 1973)

Lake Name	Serial Number	Pixel Count	LANDSAT-1 MSS Bands			
			Green	Red	IR1	IR2
Nest	20	724	45.37[a]	27.24	19.79	10.34
			2.86[b]	2.38	3.61	4.12
Green	21	4,701	47.34	27.54	18.91	10.06
			3.48	2.93	2.71	3.08
Wagonga	22	1,275	58.42	35.47	38.25	15.45
			2.79	3.09	3.04	3.39
Cokato	25	434	52.32	35.20	26.85	16.04
			3.83	4.22	3.72	4.02
Buffalo	26	1,300	59.55	39.73	38.07	18.97
			3.90	4.23	4.13	3.52
Carrigan	27	98	59.77	39.97	47.26	24.08
			3.37	3.42	3.73	3.28
Silver	28	346	60.43	40.78	46.73	22.61
			3.67	4.02	3.33	3.39
Cottonwood	111	293	52.35	32.04	30.10	12.13
			1.46	1.38	3.50	3.91

[a] Mean DN value for the lake.
[b] Standard deviation of the lake DN values.

APPENDIX D11. 19 August 1972 (1027-15233)

Section D11.1. Regression Models, and Correlation Coefficients (Table D11-1)

Seven New York lakes were extracted from the frame; all were incorporated into the regression model.

Conesus (91)
Canandaigua (92)
Keuka (93)
Seneca (94)
Cayuga (95)
Owasco (96)
Cross (97)

TABLE D11-1. CORRELATIONS BETWEEN GROUND TRUTH AND MSS DATA (COLORS AND COLOR RATIOS) FOR 7 NEW YORK LAKES EXTRACTED FROM FRAME 1027-15233 (19 AUGUST 1972).

	PC1	CHLA	LNCHLA	SECCHI	LNSECCHI
GRN	0.245	0.601	0.463	-0.792	-0.804
RED	0.772	0.833	0.664	-0.507	-0.572
IR1	0.752	0.632	0.550	0.063	-0.013
IR2	0.890	0.599	0.510	0.116	0.023
GRNRED	-0.906	-0.717	-0.580	0.072	0.158
GRNIR1	-0.596	-0.331	-0.307	-0.419	-0.356
GRNIR2	-0.740	-0.337	-0.284	-0.389	-0.315
REDIR1	-0.286	-0.032	-0.084	-0.621	-0.583
REDIR2	-0.645	-0.207	-0.186	-0.490	-0.423
IR1IR2	-0.860	-0.349	-0.268	-0.239	-0.152

The best model for the prediction of the lake trophic state index is:

$$\widehat{PC1} = -4.981 - 8.805\ GRNIR1 + 19.301\ REDIR1$$

This model explains about 83 percent of the variation about the mean (Table D11-2). The observed and predicted PC1 values are in Table D11-3.

TABLE D11-2. ANALYSIS OF VARIANCE TABLE OF THE PC1 REGRESSION MODEL FOR 7 NEW YORK LAKES EXTRACTED FROM FRAME 1027-15233 (19 AUGUST 1972).

Source	Analysis of Variance			
	df	Sum of Squares	Mean Square	Calculated F
Total (corrected)	6	12.741	2.124	
Regression	2	10.552	5.276	9.645
Residual	4	2.189	0.547	

$R^2 = 0.8282 \times 100 = 82.82\%$ s.e. of estimate = 0.740

TABLE D11-3. PC1 RESIDUALS OF 7 NEW YORK LAKES EXTRACTED FROM FRAME 1027-15233 (19 AUGUST 1972).

Lake Name	Serial Number	PC1	$\widehat{PC1}$	$PC1-\widehat{PC1}$
Conesus	91	-1.41	-1.82	0.41
Canandaigua	92	-3.63	-2.67	-0.96
Keuka	93	-2.14	-2.82	0.68
Seneca	94	-2.89	-2.58	-0.31
Cayuga	95	-2.74	-3.28	0.52
Owasco	96	-2.47	-1.98	-0.49
Cross	97	0.86	0.73	0.13

Section D11.2. Three-dimensional Color Ratio Model

The MSS color ratio is displayed in Figure D11-1. Lake Canandaigua appears to be misplaced if its PC1 value is an accurate assessment of its trophic state.

Section D11.3. Concatenation of Extracted Lakes

The concatenation of seven lakes is found in Figure D11-2.

Section D11.4. MSS-Lake Surface Area Relationships

The areal aspects of the seven lakes are in Table D11-4.

Section D11.5. Lake MSS Descriptive Statistics

The MSS statistics are in Table D11-5.

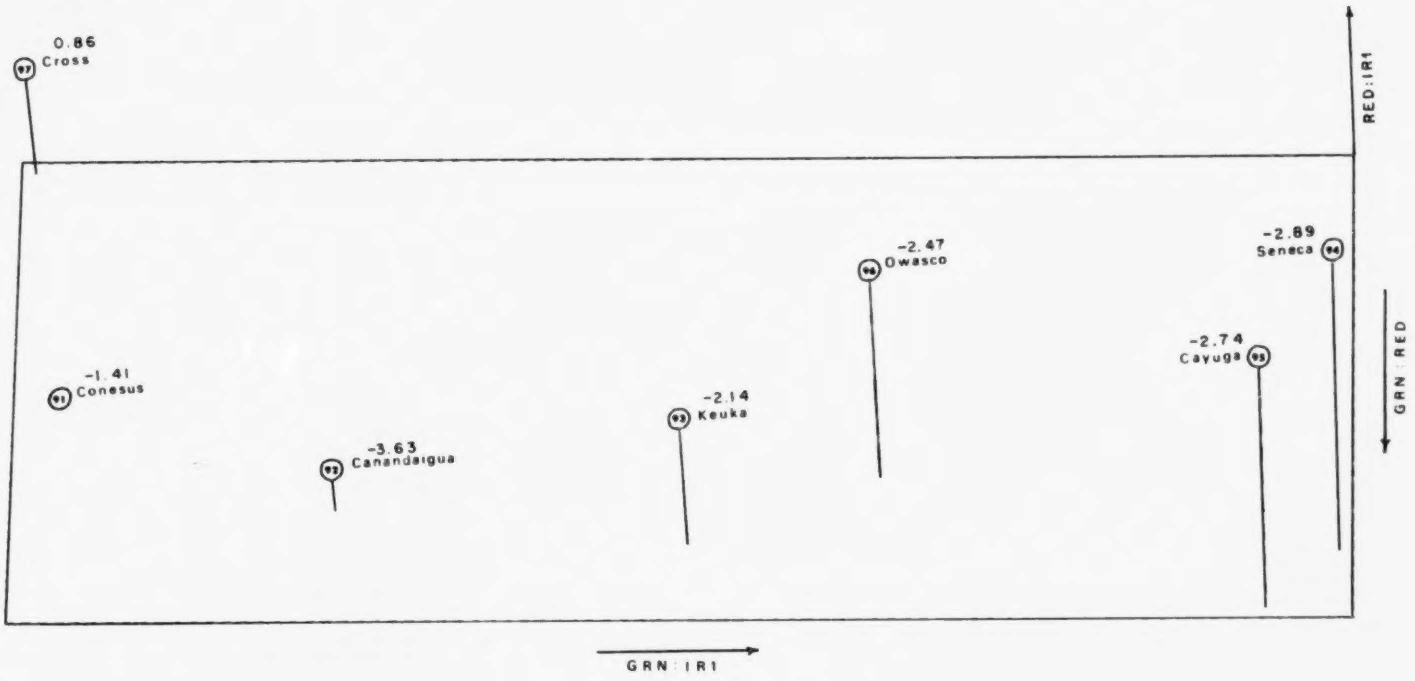


Figure D11-1. Three-dimensional MSS color ratio model of 7 New York lakes extracted from Frame 1027-15233 (19 August 1972).

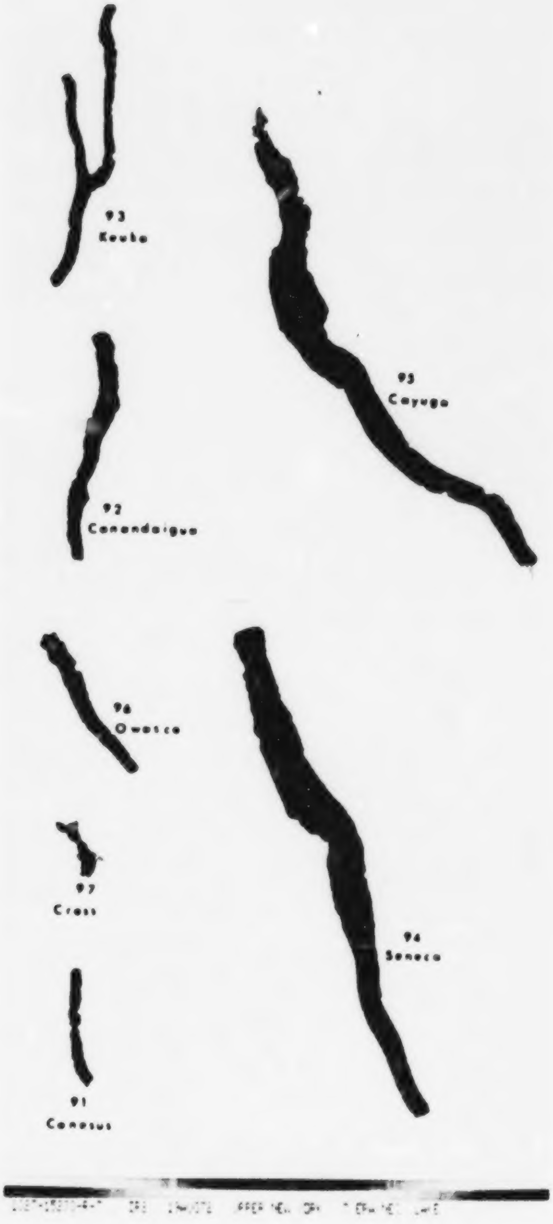

93
Keuka
95
Cayuga
92
Canandaigua
96
Owasco
97
Cross
94
Seneca
91
Conesus

Figure D11-2. IR2 concatenation of 7 New York lakes extracted from Frame 1027-15233 (19 August 1972).

TABLE D11-4. AREAL ASPECTS OF 7 NEW YORK LAKES EXTRACTED FROM FRAME 1027-15233 (19 AUGUST 1972).

Lake Name	Serial Number	Pixel Count	LANDSAT-1 Lake Area (ha)	Map Lake Area (ha)	Map Area: LANDSAT-1 Area Ratio
Conesus	91	2,764	1,319.9	1,347.3	1.021
Canandaigua	92	9,009	4,302.2	4,219.8	0.998
Keuka	93	9.896	4,725.8	4,739.9	1.003
Seneca	94	37,782	17,583.9	17,252.5	0.981
Cayuga	95	37,339	17,831.1	17,319.9	0.971
Owasco	96	5,835	2,786.5	2,745.5	0.985
Cross	97	1,712	817.6	844.4	1.033

TABLE D11-5. MSS DESCRIPTIVE STATISTICS FOR 7 NEW YORK LAKES EXTRACTED FROM FRAME 1027-15233 (19 AUGUST 1972).

Lake Name	Serial Number	Pixel Count	LANDSAT-1 MSS Bands			
			Green	Red	IR1	IR2
Conesus	91	2,764	37.38[a] 2.12[b]	19.67 2.21	16.47 3.49	7.83 4.14
Canandaigua	92	9,009	40.17 3.14	20.20 2.68	16.32 2.04	6.05 3.83
Keuka	93	9,896	38.49 2.32	19.09 2.19	14.23 3.37	5.99 4.09
Seneca	94	37,782	42.53 2.68	21.02 1.99	13.49 3.61	5.04 3.45
Cayuga	95	37,339	41.11 1.92	19.86 3.01	13.25 3.41	5.11 3.42
Owasco	96	5,835	40.79 4.00	20.78 4.05	14.38 3.72	5.94 3.81
Cross	97	1,712	43.25 3.62	25.34 3.16	19.26 4.10	9.11 4.68

[a] Mean DN value for the lake.
[b] Standard deviation of the lake DN values

APPENDIX D12. 11 October 1972 (1080-15180)

Section D12.1. Regression Models and Correlation Coefficients

Five lakes were extracted from the frame. No regression models were constructed due to the small number of observations. Correlation coefficients between ground truth and MSS data were not determined for the same reason.

Section D12.2. Three-dimensional Color Ratio Model

The MSS color ratio model is displayed in Figure D12-1. The large shift in position of Lake Cayuga (95) - compare with Figure 58 - may be a consequence of the thin cloud deck over it.

Section D12.3. Concatenation of Extracted Lakes

The extracted lakes are in Figure D12-2. Lakes Cross and Cayuga are only partially in the sensor field of view; this accounts for the linear "shore lines".

Section D12.4. MSS-Lake Surface Area Relationships

The areal aspects of the lakes are in Table D12-1.

Section D12.5. Lake MSS Descriptive Statistics

The MSS statistics are in Table D12-2.

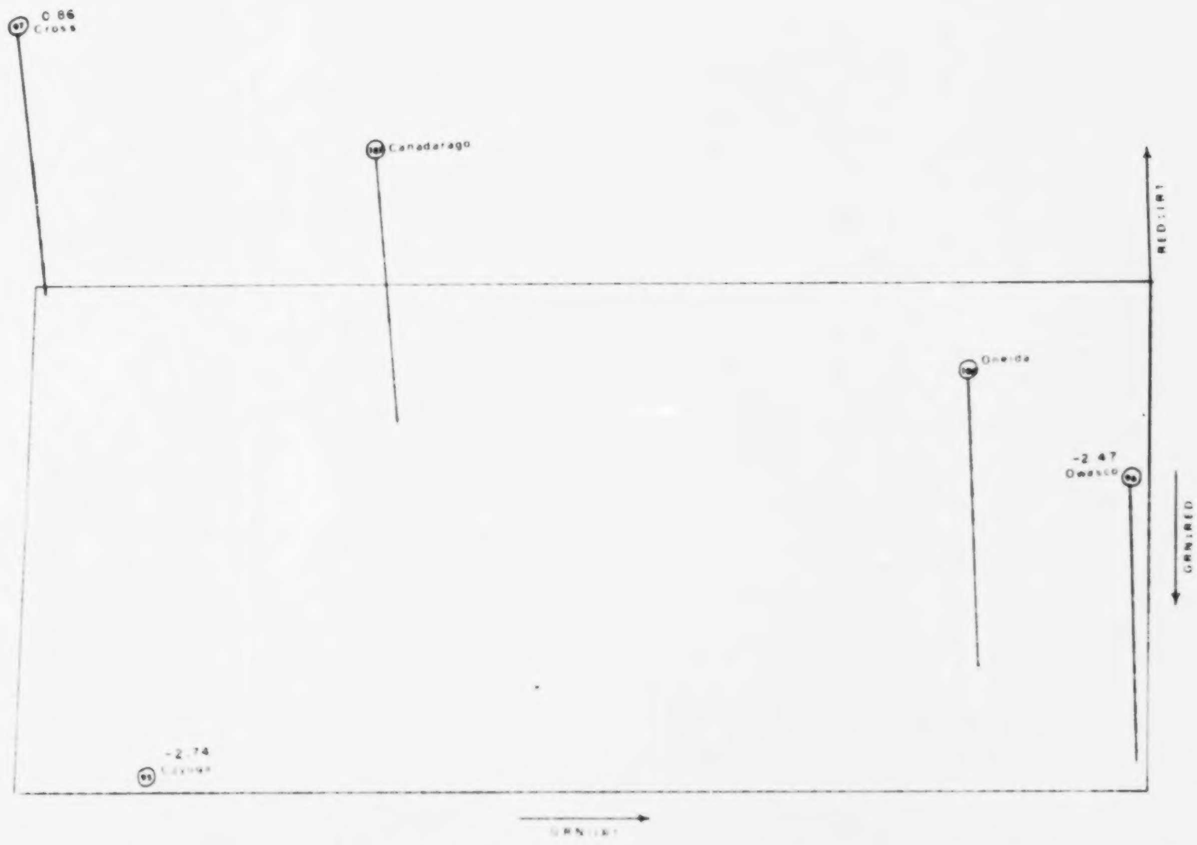


Figure D12-1. Three-dimensional MSS color ratio model of five New York lakes extracted from Frame 1080-15180 (11 October 1972).

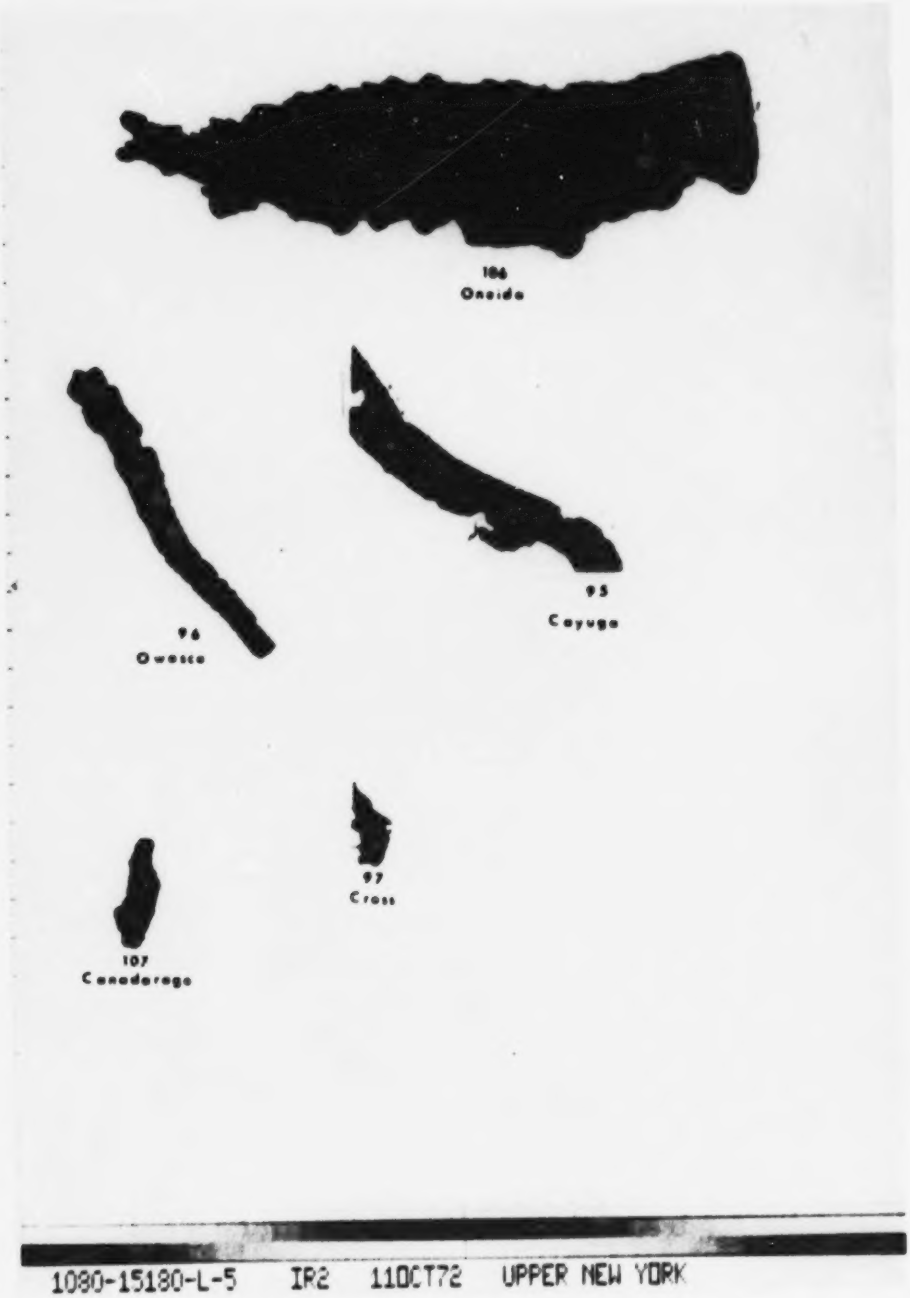

106
Oneida
96
Owasco
95
Cayuga
97
Cross
107
Canadarago
1080-15180-L-5 IR2 11OCT72 UPPER NEW YORK

Figure D12-2. IR2 concatenation of five New York lakes extracted from Frame 1080-15180 (11 October 1972).

TABLE D12-1. AREAL ASPECTS OF 5 NEW YORK LAKES EXTRACTED FROM FRAME 1080-15180 (11 OCTOBER 1972).

Lake Name	Serial Number	Pixel Count	LANDSAT-1 Lake Area (ha)	Map Lake Area (ha)	Map Area: LANDSAT-1 Area Ratio
Cayuga	95	8,799	4,206.0	17,319.9	---[a]
Owasco	96	6,018	2,876.6	2,745.5	0.955
Cross	97	1,072	512.4	844.4	---[a]
Oneida	106	44,934	21,478.5	20,720.6	0.963
Canadarago	107	1,644	785.8		

---

[a] Only a fraction of the lake surface is in the sensor field of view.

TABLE D12-2. MSS DESCRIPTIVE STATISTICS FOR 5 NEW YORK LAKES EXTRACTED FROM FRAME 1080-15180 (11 OCTOBER 1972).

Lake Name	Serial Number	Pixel Count	LANDSAT-1 MSS Bands			
			Green	Red	IR1	IR2
Cayuga	95	8,799	36.31[a]	18.18	12.49	6.23
			2.72[b]	2.89	4.88	5.63
Owasco	96	6,018	38.66	19.46	11.40	4.53
			2.94	3.63	3.75	4.00
Cross	97	1,072	38.68	22.63	13.58	4.93
			1.28	3.01	3.87	4.68
Oneida	106	44,934	34.89	18.07	10.53	4.17
			2.11	2.15	2.77	2.93
Canadarago	107	1,664	35.53	19.89	11.75	4.63
			2.18	2.62	4.20	

[a] Mean DN value for the lake.
[b] Standard deviation of the lake DN values.

APPENDIX E

N x N SQUARED EUCLIDIAN DISTANCE MATRIX

The dendrogram of 100 NES-sampled lakes (Figure 15) was created using the output of the McKeon hierarchical cluster analysis program. The clustering procedure was carried out using the matrix in this appendix. Only the lower triangular form of the matrix is reproduced here.

```
MCKEON CLUSTER ANALYSIS VERSION 1.1

CONTROL INPUT: 100   3   6   2   2   1   2
             1(3X,6F10.5)

FIRST ROW OF DATA FOR VERIFICATION-
  2.678E 00  -5.413E-01   5.497E 00  -2.974E 00  -2.206E-01   7.655E-01
SQUARED DISTANCES BETWEEN POINTS BEFORE CLUSTERING

          1         2         3         4         5         6         7         8         9        10        11        12        13        14        15
  1       0
  2    .633         0
  3    .511      .720         0
  4   1.052     1.490      .505         0
  5   1.191      .571      .542     1.511         0
  6   2.536     1.271     1.730     3.307      .395         0
  7   2.250     1.551     1.650     2.961      .695      .679         0
  8   2.244      .760     1.756     2.522      .951     1.244      .962         0
  9   1.564     2.666     1.439      .431     3.280     5.833     5.290     4.401         0
 10   1.319     2.450     2.050     2.568     2.589     3.605     2.155     3.515     3.528         0
 11   4.698     6.044     4.580     5.190     4.318     4.884     2.840     6.188     7.165     1.847         0
 12   5.566     7.828     6.684     6.858     7.412     8.634     5.540     8.561     7.854     1.642     1.421         0
 13    .963     1.131      .896     1.776      .785     1.617      .566     1.314     3.177     1.278     2.697     4.419         0
 14   1.648     1.209     2.736     4.672     2.396     2.571     3.070     2.707     5.927     3.232     7.943     8.772     2.622         0
 15   4.553     6.822     5.087     5.238     5.425     6.758     6.605     9.630     6.036     4.071     3.375     5.368     5.156     8.601         0
 16   2.032     1.002     1.856     3.473     1.110     1.441     2.634     1.968     5.008     5.383     8.718    12.168     2.370     1.741     8.136
 17   3.929     1.900     2.991     5.214     1.409      .496     1.552     1.361     7.975     5.865     8.189    12.181     2.790     2.568    11.240
 18   2.501     1.469     2.072     3.294      .851      .952     2.373     2.379     5.216     5.128     6.931    11.120     2.526     3.021     5.661
 19   4.325     2.385     3.705     4.818     3.191     3.481     6.090     3.777     6.163     8.991    14.415    18.137     6.215     3.638    12.471
 20    .936     1.498     1.477     1.840     3.097     5.192     5.376     4.397     1.444     4.005     9.164     9.789     3.156     2.907     7.214
 21   2.988     1.033     2.687     3.402     1.436     1.375     1.497      .204     5.512     4.293     7.490     9.896     2.281     2.689    11.161
 22  22.133    35.375    23.284    19.575    29.635    35.780    36.401    11.351    14.676    28.494    39.817    36.582    30.258    29.357    30.971
 23    .657      .597      .489     1.350     1.129     2.342     2.727     1.980     2.011     3.337     7.456     9.325     1.713     1.807     7.336
 24  22.071    35.930    23.830    19.209    30.077    36.507    36.287    31.833    14.262    26.981    36.976    32.902    29.806    30.526    28.023
 25   8.173     6.436     7.887     7.886    10.366    12.829    12.407     8.642     6.556     9.523    19.213    16.559     9.711     6.218    19.590
 26   5.819     8.049     7.981     7.092    11.475    15.212    14.650    11.985     4.606     9.423    17.976    15.137    10.320     8.627    14.305
 27  21.351    25.121    23.003    19.342    29.426    35.476    35.836    31.508    14.417    26.603    37.467    33.579    29.636    28.481    28.756
 28  23.866    29.066    26.324    23.662    33.403    39.725    40.050    17.009    18.172    29.290    40.661    35.882    32.866    30.496    29.962
 29   1.530     2.119     2.532     3.000     3.686     5.317     6.562     5.317     2.742     4.821    10.686    11.363     4.669     2.445     7.009
 30   2.564     1.555     2.020     3.188      .691      .630     1.885     2.275     5.310     4.457     5.688     9.832     2.323     3.261     4.990
 31   4.567     3.223     5.379     8.133     3.440     2.396     4.110     4.569    10.609     6.205     9.321    12.213     4.862     1.609     8.987
 32   1.422     2.489     1.360     1.635     2.430     3.739     2.467     3.829     2.453      .522     2.256     2.626     1.578     4.316     4.293
 33   8.760    10.726     8.536     6.802    12.953    16.996    15.817    13.266     4.447    11.355    18.630    16.682    12.429    14.228    18.229
 34   5.909     7.561     7.815     7.722    11.063    13.889    14.202    11.679     5.839     9.156    18.537    15.790    10.899     6.965    15.510
 35   2.281     4.171     3.025     2.888     5.592     8.361     8.564     8.050     1.738     5.215    10.509    10.456     5.554     5.548     6.666
 36   4.588     5.083     6.512     6.034     8.679    11.067    10.305     7.167     4.890     6.444    15.121    12.203     7.782     5.311    15.560
 37  12.702    15.716    12.798    10.813    17.877    22.567    23.367    21.562     7.558    16.692    24.476    23.099    18.586    18.465    16.563
 38  36.761    42.866    38.066    36.615    47.677    55.855    55.516    51.166    27.557    43.687    55.890    50.561    46.610    46.502    43.655
 39   1.373     2.336     1.313     1.078     2.183     3.748     2.076     2.811     1.818      .766     2.261     2.732     1.016     4.827     4.710
 40   1.169     2.111     1.211     1.258     2.165     3.857     2.025     2.491     1.853     1.208     3.100     3.631      .857     4.315     5.728
 41   9.367    10.062     8.767     9.666     9.386     8.271     8.426    12.586    11.652     5.286     4.168     5.601     8.733    10.557     3.121
 42   7.268     9.988     8.669     8.696    10.007    11.161     9.036    12.186     9.365     3.002     4.073     1.778     7.980    10.196     6.161
 43  12.322    10.826    11.275    13.706     8.212     6.323     4.519     8.003    18.326     8.577     5.167     8.863     7.279    11.877    13.910
 44  29.181    26.758    27.407    31.161    22.466    18.838    16.490    22.066    17.900    22.704    15.198    20.460    21.185    27.697    27.000
 45   2.716     4.360     3.266     2.756     5.223     7.487     4.856     5.083     2.860     1.726     4.825     3.267     2.965     6.309     8.351
 46   1.169     1.078      .938     2.255      .360      .692      .972     2.012     3.986     2.280     3.551     6.517      .798     2.191     3.796
 47   4.370     6.701     4.492     4.095     7.917    10.875    10.778    10.326     2.796     6.572    12.328    11.622     7.966     8.249     9.885
 48   3.220     5.337     2.837     2.169     5.815     8.777     8.212     8.065     1.262     5.216     9.361     9.592     5.610     8.041     7.768
 49   6.350     9.497     7.102     5.565    11.356    15.559    14.697    13.686     3.082     9.105    15.362    13.567    10.666    12.016    11.571
 50   6.285     3.503     5.557     7.835     2.812     1.290     3.058     2.969    11.291     7.932     9.663    14.619     5.125     4.063    11.675
 51   5.998     3.099     5.836     7.215     3.665     3.065     3.122     1.366     9.885     7.664    10.679    13.600     4.285     4.365    15.287
 52   3.211     3.118     3.972     3.857     5.566     7.443     6.252     3.786     3.659     4.703    11.361     9.857     4.686     4.197    14.366
 53  11.689    15.151    12.984    10.366    18.115    23.223    22.882    20.228     6.717    15.686    24.023    21.256    17.664    18.125    17.766
 54   3.068     4.377     3.487     2.318     6.202     9.451     8.760     6.817      .967     6.171    12.033    11.459     5.702     7.119    10.479
```

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
55	3.091	1.405	2.293	3.842	.893	.843	2.250	1.018	6.095	5.932	8.270	12.722	2.932	2.795	8.224
56	8.200	9.626	10.169	8.836	13.723	17.709	16.927	12.687	6.167	12.659	22.309	19.360	12.575	10.932	19.969
57	5.089	2.986	3.651	5.336	1.915	1.403	3.691	3.316	7.954	8.568	10.384	16.150	4.813	4.859	9.717
58	7.669	4.562	7.192	10.031	4.522	2.853	5.610	4.708	13.281	10.666	14.168	10.984	7.580	4.006	14.787
59	2.756	1.568	2.204	4.167	1.984	2.399	2.858	1.816	5.676	5.911	10.857	17.864	2.657	2.081	12.870
60	1.100	.378	.666	2.029	.345	.654	1.165	1.022	1.665	[illegible]	5.803	8.364	1.284	1.338	7.120
61	4.125	4.405	4.494	4.097	6.933	9.477	8.761	5.806	[illegible]	2.831	14.515	13.370	6.545	6.019	15.021
62	2.252	2.495	3.207	4.523	4.140	5.514	6.898	5.491	[illegible]	6.172	12.752	13.851	5.087	1.978	9.840
63	11.530	13.762	12.309	9.802	17.274	22.154	21.519	17.492	[illegible]	15.422	25.294	22.465	16.825	17.103	21.589
64	3.111	1.170	2.507	4.305	1.360	1.134	2.305	1.271	6.649	6.092	9.695	13.297	2.979	1.910	10.997
65	7.676	4.485	6.079	8.156	3.180	1.065	3.668	3.062	11.863	10.296	10.935	17.014	5.620	6.344	13.624
66	5.095	6.972	6.202	5.260	9.667	13.481	12.562	9.894	3.181	8.981	16.307	14.766	8.491	8.031	14.029
67	6.039	7.416	5.608	4.759	7.595	10.051	12.318	11.648	4.838	10.327	14.679	17.172	10.094	10.522	6.979
68	4.870	2.448	4.027	6.109	1.850	.961	2.5	2.128	9.811	7.532	9.627	16.586	3.946	3.404	10.989
69	15.765	11.669	12.830	15.059	8.457	5.997	7.612	8.582	20.389	16.450	13.643	21.929	11.344	14.926	18.792
70	21.170	16.864	19.825	20.417	14.144	11.215	11.161	11.073	26.148	19.146	17.168	22.834	15.942	19.369	27.082
71	3.713	2.687	2.697	4.181	1.051	.633	1.787	3.045	4.854	5.075	4.988	9.862	2.713	4.515	5.065
72	4.033	3.334	2.202	2.104	3.078	4.008	3.914	2.639	3.082	6.323	9.098	11.846	3.425	7.283	12.529
73	2.696	1.495	1.666	2.415	1.813	2.772	2.442	.983	3.692	5.173	8.792	11.286	2.171	3.778	12.024
74	1.381	1.159	1.586	1.809	2.547	4.038	3.216	1.637	2.214	2.962	7.084	8.000	2.103	2.637	10.481
75	12.388	14.671	15.989	15.185	20.861	24.045	23.653	19.561	11.817	16.560	20.537	23.338	18.612	13.367	24.353
76	7.037	8.526	8.319	6.432	11.917	15.846	14.254	10.698	4.155	9.881	17.975	14.936	10.460	11.029	17.671
77	8.931	5.796	7.785	10.787	4.478	2.368	4.672	5.134	14.864	10.796	11.808	17.767	7.338	5.963	13.835
78	3.841	4.786	5.095	4.381	7.571	10.541	9.217	6.353	3.862	6.512	13.793	11.820	6.219	6.155	14.376
79	2.562	2.126	2.165	2.403	3.455	5.312	5.827	3.481	2.481	6.681	12.569	14.172	4.337	4.121	12.266
80	4.035	3.785	4.792	4.443	6.602	8.855	8.846	4.691	3.828	6.847	14.388	13.141	6.840	5.188	16.232
81	1.107	.658	1.439	2.450	1.712	2.847	3.167	1.758	3.896	4.228	8.962	10.576	2.815	1.409	9.876
82	1.813	.985	1.978	2.943	2.388	3.430	4.021	2.013	3.546	5.478	10.925	12.654	2.987	1.860	11.052
83	3.869	4.269	4.031	3.687	6.549	9.200	8.947	6.079	2.644	7.375	14.721	14.181	6.611	6.119	14.756
84	2.520	2.177	1.508	1.196	2.781	4.789	5.110	3.156	1.389	6.052	10.592	12.813	3.889	5.411	10.384
85	4.043	4.103	5.346	5.178	7.298	9.488	8.789	5.608	4.391	6.557	14.663	12.679	6.623	4.645	15.953
86	5.388	6.541	6.000	4.615	9.258	12.849	12.029	8.761	2.756	9.806	16.665	15.145	8.650	9.150	15.617
87	25.252	23.781	23.250	26.287	18.687	15.586	13.874	20.152	32.518	19.321	11.366	17.378	18.195	25.397	20.835
88	1.983	3.329	2.604	3.515	2.608	3.352	2.150	4.561	4.871	.642	.929	1.850	1.400	4.861	2.161
89	2.441	2.220	1.939	2.815	1.677	2.368	.631	1.381	4.583	2.209	3.152	4.934	.489	4.189	8.020
90	2.103	3.063	2.039	2.583	2.495	3.710	1.581	2.985	3.787	1.071	1.608	2.481	.645	4.903	5.631
91	3.453	1.759	2.430	3.486	1.068	1.184	1.194	.698	5.789	5.406	6.696	10.732	1.743	4.241	9.569
92	20.187	15.770	16.489	17.186	12.349	10.675	10.688	10.767	22.346	20.451	16.548	24.834	14.391	21.830	24.288
93	9.146	7.447	7.158	8.843	5.710	5.468	3.325	4.187	12.075	8.825	7.988	11.902	4.671	10.224	16.852
94	19.975	14.725	16.114	16.875	12.376	11.162	12.874	10.636	21.252	24.083	23.336	32.578	16.048	20.739	27.895
95	12.268	8.077	9.468	16.978	6.069	4.296	6.208	5.562	15.361	14.256	14.844	21.369	9.533	11.626	18.028
96	9.081	6.702	6.417	7.569	3.928	3.243	3.470	4.432	11.254	10.109	7.877	14.630	5.424	10.053	11.799
97	4.214	3.641	3.651	2.515	5.226	7.711	7.971	4.558	2.846	8.410	14.340	15.686	6.192	7.415	13.748
98	.810	1.123	.595	.326	1.442	2.927	3.192	2.696	.815	2.354	5.631	7.093	2.193	3.595	4.819
99	2.569	4.488	2.886	2.228	5.441	8.461	6.535	6.057	1.355	3.925	7.944	7.238	3.694	6.873	8.848
100	1.541	1.785	1.575	2.666	1.869	2.922	1.319	1.696	3.829	2.031	4.282	5.334	.471	2.888	8.039

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
16	0														
17	1.386	0													
18	.702	1.996	0												
19	1.685	3.091	2.458	0											
20	2.764	6.084	4.223	4.032	0										
21	2.348	1.226	2.785	3.320	5.268	0									
22	29.282	38.385	31.824	24.940	15.775	32.522	0								
23	1.116	2.739	2.244	2.349	.709	2.518	21.452	0							
24	38.948	40.444	32.318	27.824	16.918	33.366	1.193	23.002	0						
25	9.144	12.010	12.858	8.385	4.123	8.674	14.002	5.507	16.184	0					
26	10.573	16.371	13.277	11.031	3.065	13.054	8.076	6.291	8.540	2.530	0				
27	29.668	38.631	31.841	25.792	15.598	32.649	.401	21.529	.808	14.044	7.539	0			
28	32.638	42.921	35.564	38.272	17.285	38.617	2.722	24.329	3.634	16.850	8.475	1.750	0		
29	2.876	6.504	3.783	2.964	.799	5.661	16.358	1.519	17.338	4.767	3.797	15.779	17.507	0	
30	1.238	2.089	.136	3.078	4.849	2.615	33.256	2.623	33.356	13.830	14.362	32.988	37.041	4.350	0
31	2.347	2.586	2.387	4.408	7.046	4.234	40.173	4.719	41.193	13.445	16.095	30.186	41.382	5.323	2.452
32	5.607	6.024	5.415	8.483	3.466	4.669	25.427	2.887	24.626	9.588	9.196	23.905	26.759	4.766	4.729
33	15.017	18.404	17.342	13.694	6.044	14.168	7.091	8.204	8.460	5.716	4.527	7.147	10.720	8.428	17.698

34	10.198	14.511	13.098	9.087	3.352	11.886	9.856	5.829	11.646	1.747	1.324	8.980	9.888	3.137	13.917
35	5.749	10.262	6.988	6.798	.746	9.181	12.022	2.544	12.720	5.633	2.440	11.361	12.064	1.397	7.458
36	8.631	11.367	11.288	8.387	3.710	7.260	14.563	5.027	15.057	.654	2.374	13.857	17.293	3.950	11.731
37	18.389	25.628	19.743	16.386	7.886	22.828	3.395	12.076	4.497	11.486	5.157	2.884	3.376	8.345	20.555
38	46.942	59.482	50.343	44.161	28.235	53.596	3.924	36.895	4.545	27.159	16.303	3.855	2.551	29.920	52.307
39	5.384	5.983	5.024	8.562	3.539	3.079	25.285	2.035	23.859	9.406	8.959	24.181	28.047	5.243	4.458
40	4.463	5.460	4.882	8.238	2.817	3.756	25.067	2.242	24.163	8.260	7.972	24.362	27.685	5.025	4.652
41	12.821	13.044	9.567	16.107	12.961	13.011	41.286	11.732	38.324	24.562	21.935	37.736	39.634	11.413	7.909
42	15.241	15.438	13.835	19.188	11.148	12.874	33.497	11.261	30.127	17.135	15.393	29.632	31.451	11.212	12.237
43	12.363	7.529	10.686	18.641	19.324	8.360	64.816	14.094	63.137	29.094	33.650	63.232	68.483	20.762	9.013
44	28.144	20.703	24.415	37.013	39.846	22.345	98.801	32.330	95.095	53.247	59.026	96.407	102.886	40.935	21.938
45	9.458	9.364	9.369	11.769	4.112	6.241	22.010	4.338	20.771	6.908	6.788	20.701	23.954	6.516	8.926
46	1.248	2.868	.886	4.276	3.238	2.717	31.298	1.589	31.343	11.655	11.726	30.659	33.400	3.630	.662
47	9.308	12.775	10.786	9.215	2.538	11.191	10.671	4.295	12.108	6.124	3.798	9.859	10.950	3.661	11.011
48	7.719	10.904	8.629	8.644	2.036	9.293	12.489	3.261	13.228	7.308	4.623	12.034	13.988	3.873	8.762
49	12.593	18.073	14.175	13.124	3.729	15.030	6.530	6.885	6.697	6.730	2.205	5.898	7.001	5.431	14.730
50	2.781	1.148	2.129	3.942	9.602	2.359	44.735	5.602	46.008	16.678	21.245	44.680	49.925	8.467	1.875
51	3.547	2.111	4.169	5.463	8.907	1.115	41.114	5.455	41.752	11.948	17.562	41.640	48.155	9.243	4.243
52	6.354	7.297	8.746	6.861	3.161	3.973	10.759	3.114	19.788	1.621	4.616	18.526	22.850	4.489	9.088
53	18.808	26.067	20.618	17.507	7.625	21.677	2.275	12.112	2.417	8.735	3.076	1.795	3.161	8.678	21.492
54	6.828	10.801	8.411	7.345	1.438	7.748	10.065	3.002	10.458	3.601	1.888	10.175	13.334	3.032	9.027
55	.559	.898	.354	1.611	4.716	1.869	33.225	2.137	34.699	12.186	14.325	33.577	37.836	4.371	.511
56	12.382	17.940	15.865	12.013	4.901	13.609	7.876	7.946	8.865	1.869	.884	8.173	10.622	6.142	17.204
57	1.417	1.590	.853	1.925	6.628	3.279	35.925	3.559	37.963	15.534	17.691	36.663	41.255	6.115	1.030
58	2.980	1.889	3.139	2.966	9.885	3.814	43.727	6.146	46.398	15.712	20.916	43.946	48.362	8.040	3.308
59	.986	1.248	2.953	2.684	3.869	2.119	29.560	1.152	32.379	7.162	10.466	30.388	33.344	4.321	3.561
60	.868	1.005	1.399	2.381	2.471	1.231	28.368	.620	29.723	8.075	10.173	28.188	31.650	2.916	1.400
61	7.156	9.224	10.011	6.729	2.556	6.181	13.366	3.216	15.307	1.202	3.134	13.694	17.465	4.191	10.634
62	2.150	5.549	4.038	2.663	1.015	5.833	19.115	1.434	21.359	4.514	4.595	19.039	20.040	.632	4.984
63	17.662	23.651	20.371	15.633	7.410	18.523	2.730	11.073	3.724	5.641	2.816	3.050	6.185	9.015	21.384
64	.537	.451	1.386	1.466	4.361	1.146	32.708	1.796	34.862	9.351	12.979	33.264	37.473	4.366	1.733
65	3.186	1.329	2.496	4.576	10.758	2.811	46.475	6.265	48.122	18.931	23.542	47.336	53.402	10.631	2.418
66	9.113	14.302	11.011	10.005	2.367	11.264	8.638	4.938	9.447	2.960	.736	8.869	10.635	4.243	12.916
67	7.920	13.148	7.055	6.621	4.449	12.469	13.326	5.751	13.963	13.176	8.398	13.107	15.412	3.581	7.443
68	1.236	.586	1.140	2.598	7.146	1.944	39.762	3.733	41.671	14.311	17.967	40.242	44.967	6.725	1.267
69	10.296	6.131	7.886	12.721	21.229	8.200	64.857	14.662	65.568	33.124	38.607	65.634	73.635	21.355	7.003
70	17.865	11.246	15.327	19.771	28.733	9.968	73.305	21.376	72.202	35.322	44.422	73.274	84.543	28.520	13.698
71	2.148	2.139	.673	4.603	6.610	3.460	38.048	3.786	38.173	17.170	17.801	37.695	41.657	6.402	.309
72	4.881	4.758	5.905	5.886	4.341	3.429	24.115	2.009	25.816	8.952	11.063	25.231	30.757	7.161	6.005
73	2.256	2.189	3.776	3.627	1.227	1.445	26.533	1.316	28.469	6.826	9.981	27.436	32.250	5.186	4.090
74	3.404	4.197	5.038	4.628	1.857	2.037	21.005	1.198	21.859	3.330	5.611	20.917	25.083	3.213	5.209
75	17.814	24.332	22.008	17.032	8.504	20.096	9.386	12.799	10.561	3.212	1.967	8.540	8.662	8.394	23.488
76	12.631	16.804	15.286	12.481	4.861	11.647	8.442	7.297	8.554	2.476	1.788	8.404	12.193	6.689	16.003
77	4.189	1.911	3.328	5.434	12.408	4.437	51.186	7.798	53.150	21.862	26.077	51.273	56.115	11.214	3.071
78	7.569	10.805	10.266	8.508	2.479	7.189	13.181	3.889	13.758	1.285	1.761	13.193	16.422	4.163	11.020
79	2.792	4.987	4.808	2.566	1.230	3.856	16.658	.955	19.116	3.669	5.059	17.605	21.318	2.434	5.598
80	6.487	8.367	9.268	6.386	1.030	4.956	15.999	1.381	17.429	.999	3.663	16.365	20.766	4.372	9.925
81	.832	2.687	2.387	2.408	1.145	2.276	23.086	.433	24.559	4.788	6.199	23.377	26.299	1.867	3.032
82	1.104	2.868	2.956	1.867	1.465	2.327	22.198	.645	24.263	4.198	6.205	22.802	26.160	2.085	3.717
83	6.514	9.140	9.164	5.812	1.905	6.545	11.776	2.727	13.963	1.667	2.777	12.263	15.726	3.389	9.891
84	3.310	5.205	4.375	3.020	1.733	3.738	16.726	1.183	18.489	5.835	6.487	17.601	22.209	3.098	4.811
85	7.029	9.158	9.892	6.856	3.037	5.738	15.617	3.761	16.922	.432	2.926	15.473	19.154	3.843	10.518
86	9.456	13.503	12.003	9.035	2.932	9.684	8.267	4.857	9.337	2.333	1.651	8.667	12.152	4.723	12.849
87	24.838	18.297	20.625	32.871	34.964	20.661	89.703	28.053	86.525	50.775	54.403	87.306	92.888	36.076	18.098
88	5.252	6.059	4.311	10.028	5.167	5.662	33.120	4.272	31.170	13.644	12.288	31.119	33.022	5.887	3.616
89	3.869	3.068	4.287	8.084	5.116	2.263	34.027	2.995	33.713	10.960	12.943	33.675	37.830	7.474	3.936
90	5.389	5.410	5.497	10.270	4.752	4.299	31.413	3.552	30.198	11.312	11.409	30.350	33.415	7.174	4.978
91	1.663	1.263	1.681	4.295	5.713	1.249	35.658	2.825	36.270	12.593	15.223	36.325	41.661	6.978	1.732
92	15.698	11.040	12.985	18.559	26.082	10.960	67.335	19.216	66.791	37.310	42.979	68.894	79.730	27.891	11.936
93	8.138	4.726	8.052	13.217	12.773	5.102	49.529	8.468	50.409	19.545	24.683	50.264	55.942	16.574	8.410
94	12.810	10.011	11.505	13.067	23.085	10.530	58.326	16.881	60.298	32.441	38.478	61.425	72.080	24.361	11.535
95	7.327	4.040	5.726	7.435	16.149	4.904	52.151	10.462	53.733	24.472	30.817	53.341	61.924	15.926	5.167
96	6.037	4.048	4.321	9.321	12.883	5.115	48.736	8.292	48.877	24.397	26.894	49.609	56.315	14.483	3.783
97	5.363	8.086	6.740	4.282	2.862	5.094	13.691	2.908	15.038	4.697	5.437	14.878	20.528	4.100	7.419
98	3.092	4.885	2.802	3.705	1.628	3.204	19.263	1.190	19.140	7.251	6.717	18.691	22.735	1.851	2.634
99	7.132	9.921	8.738	9.945	1.999	7.625	15.756	3.077	15.731	5.570	3.899	15.410	17.639	4.801	9.011

100	3.115	3.292	4.333	7.243	3.220	2.733	29.909	1.916	30.168	8.838	9.542	29.555	32.416	5.520	4.342
	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
31	0														
32	7.869	0													
33	23.562	8.631	0												
34	13.799	8.653	4.699	0											
35	10.415	4.188	4.955	2.840	0										
36	11.958	7.123	5.637	1.950	4.931	0									
37	26.268	13.811	4.560	5.681	4.327	11.169	0								
38	60.109	40.182	16.765	20.147	21.905	28.087	8.677	0							
39	8.581	.497	8.786	9.691	4.776	6.751	14.942	40.292	0						
40	8.417	1.056	8.580	9.211	4.419	6.256	15.125	39.451	.308	0					
41	9.740	5.695	23.920	19.783	12.549	19.543	23.965	57.598	7.656	10.033	0				
42	13.711	3.517	16.080	13.931	10.404	12.518	19.953	47.057	5.055	6.950	3.525	0			
43	10.260	10.084	34.256	32.399	24.236	25.204	46.187	88.681	9.645	10.263	11.558	13.772	0		
44	22.629	25.545	60.763	57.791	46.414	67.349	75.214	127.257	24.756	26.006	21.827	27.098	3.960	0	
45	12.421	1.420	6.056	7.543	4.935	4.739	13.585	35.041	1.032	1.037	11.487	5.265	13.970	31.431	0
46	2.715	2.498	14.056	11.511	5.396	9.761	10.281	48.266	2.511	2.421	6.843	9.060	8.039	21.668	5.758
47	14.595	4.475	2.507	2.882	1.177	5.672	3.331	20.437	5.815	5.913	13.913	10.037	26.827	50.591	4.913
48	13.936	3.114	2.745	4.922	1.172	6.438	4.663	22.980	3.649	3.635	12.898	9.675	22.811	44.852	3.489
49	19.871	7.208	2.070	3.616	1.724	6.022	1.951	13.456	7.464	7.199	18.767	13.043	33.245	58.717	5.788
50	1.843	8.875	24.935	10.902	14.161	14.998	31.023	68.397	8.780	8.910	12.028	17.082	7.338	17.972	13.731
51	4.884	9.132	21.290	17.164	14.336	10.589	31.304	64.058	7.436	6.730	18.133	18.619	8.467	28.381	10.424
52	10.356	4.659	5.333	4.089	5.284	1.073	13.608	34.200	4.896	3.510	17.888	11.523	18.475	38.688	2.727
53	27.230	13.502	3.129	4.794	4.627	8.234	.996	7.450	13.620	13.484	26.154	19.436	45.538	74.447	11.192
54	13.588	5.014	2.492	3.376	1.582	2.969	5.640	21.160	4.251	3.652	17.628	12.960	24.934	47.719	3.567
55	2.260	5.998	17.353	13.265	8.004	11.096	21.318	53.177	5.763	5.517	11.366	15.389	10.258	24.303	9.961
56	19.456	12.352	4.581	2.654	5.132	2.330	7.622	17.127	11.261	9.845	20.801	20.698	37.143	63.726	8.471
57	3.429	8.192	20.080	16.354	10.840	14.625	23.331	56.763	8.051	7.886	12.927	18.789	11.714	25.516	13.171
58	1.650	11.602	25.986	17.620	14.491	15.038	38.644	67.268	12.035	11.843	15.241	20.806	11.988	24.528	16.828
59	4.287	5.721	12.969	9.556	6.576	7.591	19.383	47.335	5.522	4.217	16.493	16.417	12.598	29.562	7.311
60	2.840	2.642	11.882	8.890	5.058	7.069	17.053	46.346	2.830	2.593	9.556	10.369	9.498	24.975	5.195
61	13.046	6.041	2.830	2.787	3.916	1.509	9.427	26.932	5.669	4.830	20.934	14.586	24.186	47.183	4.013
62	4.760	6.399	10.104	3.738	2.359	4.753	10.716	32.839	6.952	5.989	14.806	14.656	21.274	41.828	8.088
63	26.955	13.779	1.659	4.320	5.834	5.829	3.342	10.278	13.280	12.650	30.098	21.813	43.963	73.888	10.197
64	2.361	6.367	16.166	11.603	8.193	8.934	21.915	52.834	6.052	5.374	14.137	16.288	18.831	25.822	9.187
65	4.206	10.499	25.842	22.214	15.864	17.665	33.095	70.533	9.664	9.366	15.835	21.387	7.825	18.381	15.111
66	16.445	8.130	3.214	2.782	2.288	3.106	5.566	17.466	7.326	6.040	22.837	16.534	30.938	55.870	5.536
67	12.976	8.369	9.482	8.469	3.028	11.796	5.115	24.950	9.046	9.695	12.744	15.677	29.185	50.931	11.893
68	2.073	8.068	21.621	16.560	11.450	13.293	27.116	61.646	7.678	7.262	13.424	17.922	8.871	21.297	12.235
69	10.511	16.732	38.396	37.080	27.380	30.535	47.971	92.768	15.616	16.068	18.928	27.322	6.390	11.769	23.166
70	16.137	20.705	43.078	42.215	36.075	31.296	58.728	105.053	18.774	20.001	23.760	28.073	6.733	9.669	24.867
71	3.065	5.096	20.253	17.108	9.357	14.886	23.556	57.723	5.047	5.368	7.266	12.499	7.177	18.677	10.059
72	11.704	4.532	7.437	11.430	6.889	8.576	16.059	41.089	3.517	2.895	17.691	15.572	14.313	32.392	4.735
73	7.171	4.474	9.658	9.842	6.537	6.655	17.954	44.480	3.586	2.653	16.697	15.130	12.171	29.304	4.972
74	7.203	2.789	6.421	5.367	4.139	2.536	13.767	37.054	2.216	1.675	14.195	10.314	14.022	32.367	2.242
75	22.304	16.997	8.722	2.261	7.770	3.835	9.154	16.668	17.171	15.885	31.495	22.288	45.376	73.689	13.137
76	19.918	9.023	2.227	3.406	4.956	2.014	7.457	18.716	7.875	7.144	24.871	16.881	32.176	57.193	5.072
77	2.555	11.632	29.899	23.118	17.422	19.653	35.631	75.855	11.918	11.982	13.651	20.544	7.862	17.448	17.737
78	13.327	6.371	3.980	2.955	3.685	1.022	9.768	25.225	5.349	4.271	21.889	13.992	24.622	47.139	3.503
79	8.554	5.589	5.887	4.921	3.162	4.108	10.464	31.714	5.114	4.131	18.312	16.318	28.285	41.500	5.772
80	11.671	6.641	4.912	3.687	5.163	1.021	12.401	30.821	5.716	4.759	21.468	15.175	22.427	44.187	4.309
81	4.220	4.405	10.871	6.267	3.705	4.502	14.561	38.975	3.886	2.849	14.382	13.514	14.591	32.548	5.277
82	4.888	5.459	9.679	6.030	4.192	4.305	14.519	38.587	4.918	3.812	16.426	15.428	16.312	35.125	6.191
83	12.797	6.074	2.489	2.521	2.917	2.105	7.626	24.812	5.831	5.806	20.432	15.165	25.157	48.763	4.630
84	9.585	4.476	5.284	6.602	3.299	5.564	9.989	32.158	3.877	3.421	16.848	14.888	18.786	39.028	5.147
85	11.127	6.665	5.232	2.451	4.818	.332	11.817	29.910	6.181	5.369	20.383	13.813	23.344	45.345	4.451
86	17.016	7.743	1.726	2.875	3.190	2.389	6.000	19.080	6.891	6.025	23.079	16.399	30.016	54.927	5.055
87	20.502	20.815	53.978	52.815	39.971	45.047	65.398	116.049	20.878	22.525	15.841	22.451	3.386	1.386	27.893
88	5.577	1.354	15.468	12.540	6.331	10.408	19.177	48.097	1.607	2.040	3.877	3.817	7.323	19.788	3.787
89	6.944	2.369	13.382	13.568	8.232	9.125	22.414	51.563	1.455	.965	11.387	9.457	5.931	19.849	3.860
90	8.307	1.169	11.966	12.395	6.688	8.920	19.424	46.586	.617	.414	8.813	6.179	7.185	20.795	1.697
91	4.913	5.604	16.959	15.733	9.748	11.241	24.533	55.718	4.228	3.584	13.975	15.715	7.603	20.492	7.734
92	19.048	20.313	39.529	43.608	32.738	34.168	53.071	95.868	17.421	17.793	26.448	32.571	9.135	14.094	24.553
93	12.131	8.627	22.468	24.958	17.977	18.375	36.182	78.726	7.114	6.067	20.045	19.869	5.123	15.496	9.608

```
  94   18.327   23.317   36.262   38.993   29.926   31.409   47.456   86.224   20.271   19.725   33.117   40.186   17.246   27.003   27.387
  95    8.876   13.957   29.600   28.817   21.671   23.151   38.724   79.232   12.906   13.360   18.783   25.412    9.132   18.388   19.305
  96    9.327    9.681   25.929   27.420   17.382   22.132   34.268   71.468    8.173    8.136   15.186   20.454    6.067   15.095   13.962
  97   12.680    7.112    4.800    6.386    4.533    4.445    9.968   28.890    5.709    5.109   20.738   17.991   23.535   45.307    6.328
  98    6.445    1.663    7.130    6.636    2.512    5.315   10.249   34.777    1.602    2.065    8.046    7.756   14.122   31.646    3.460
  99   13.474    2.881    3.708    5.584    2.328    4.646    8.702   26.418    2.332    1.590   15.239    9.746   19.533   40.142    1.371
 100    6.350    2.247   11.328   10.148    5.933    6.865   19.068   45.652    1.626     .735   12.161    9.490    8.612   23.685    2.477

           46       47       48       49       50       51       52       53       54       55       56       57       58       59       60
  46        0
  47    8.360        0
  48    6.328     .636        0
  49   11.732    1.354    1.492        0
  50    3.260   17.764   15.776   23.736        0
  51    4.874   18.119   15.509   21.795    2.477        0
  52    7.022    5.549    5.258    6.937   11.331    6.979        0
  53   18.827    4.002    4.932    1.222   31.879   29.286   10.980        0
  54    7.161    2.409    1.621    1.688   15.360   12.180    2.758    4.014        0
  55    1.387   11.297    9.357   15.554    1.251    3.129    8.095   22.268    9.070        0
  56   14.861    6.371    6.941    4.108   23.377   17.392    4.335    4.378    2.448   16.316        0
  57    2.451   13.403   11.213   18.242    1.579    4.802   11.108   25.144   11.460     .344   19.798        0
  58    4.945   18.203   17.228   24.786     .759    3.902   12.208   32.128   16.419    1.865   22.905    2.015        0
  59    2.678    8.857    7.495   12.566    4.254    3.484    4.479   19.206    6.572    1.976   11.326    3.171    4.327        0
  60     .780    6.915    5.584   10.847    2.844    3.886    4.297   17.367    5.835    1.885   12.280    2.199    3.759    1.059        0
  61    8.579    3.658    3.675    4.517   14.248   10.167     .758    7.381    1.510    9.351    2.642   12.080   14.485    5.092    5.458
  62    4.021    5.081    5.314    7.275    8.167    8.642    4.876   11.151    4.176    4.149    6.581    5.785    6.965    2.816    2.864
  63   18.990    4.865    5.535    2.261   29.922   25.186    7.685    1.183    3.040   21.031    2.268   24.810   30.035   16.644   16.116
  64    2.883   11.146    9.619   15.450    1.567    2.016    5.987   22.110    8.470     .502   14.135    1.287    1.729     .815     .866
  65    4.057   19.708   16.842   25.252     .765    2.442   12.794   33.810   14.002    1.452   24.886    1.277    1.968    4.219    3.652
  66   10.342    3.481    3.248    1.796   19.861   15.513    3.865    3.396     .721   12.600     .979   15.515   20.178    8.412    8.754
  67    7.628    4.551    4.099    5.601   14.921   18.445   12.178    7.515    5.523    8.496   11.757    8.897   15.132   11.071    7.955
  68    2.337   15.282   13.028   20.209     .472    2.162    9.696   27.842   12.388     .391   19.677     .673    1.037    2.407    1.870
  69    9.482   31.201   26.464   38.312    4.130    7.291   23.210   49.288   27.369    6.721   48.570    5.711    7.092   11.976   10.884
  70   16.208   39.026   34.361   46.149    8.338    8.124   23.999   57.190   33.076   13.535   44.807   13.916   12.555   18.460   15.612
  71     .886   12.731   10.889   17.216    1.937    5.180   11.245   25.023   11.426     .988   21.164    1.220    3.804    4.431    1.992
  72    4.923    7.118    4.545    9.348    9.014    6.629    4.267   15.175    4.372    5.117   11.011    6.216   11.129    3.213    3.152
  73    3.221    7.942    5.886   10.717    5.597    3.353    3.822   16.896    4.723    2.856   10.046    4.196    6.866     .937    1.420
  74    3.662    5.110    4.066    7.884    7.628    4.738     .627   11.952    2.487    4.689    6.044    6.951    8.851    2.293    1.850
  75   20.394    8.829   11.448    6.928   29.607   24.585    8.188    6.280    7.016   22.684    2.898   27.014   27.729   16.963   17.460
  76   13.462    4.952    4.980    3.839   22.301   16.208    2.872    4.880    1.499   15.697    1.889   19.211   23.263   11.217   10.917
  77    4.725   21.257   19.169   28.367     .417    4.311   15.314   37.432   19.576    2.212   28.701    2.804     .879    5.701    4.475
  78    8.679    4.732    4.371    4.083   15.634   10.402    1.071    6.717    1.133   10.406    1.399   13.633   16.327    6.224    6.508
  79    4.755    4.393    3.555    6.067    8.805    6.932    2.586    9.876    1.973    4.256    5.174    5.675    8.777    2.002    2.565
  80    8.256    5.865    5.568    6.489   12.665    7.735     .379    9.588    2.175    8.612    2.743   11.459   13.085    4.683    5.245
  81    2.153    6.455    5.307    8.568    5.339    3.983    2.987   13.762    3.572    2.236    7.225    3.927    5.615     .843    1.089
  82    3.089    6.681    5.732    8.917    5.631    4.052    2.738   13.733    3.641    2.471    6.799    4.035    5.515     .813    1.432
  83    8.081    2.811    2.818    3.623   14.088   10.836    1.469    6.215    1.845    8.667    2.578   10.952   14.094    4.899    5.195
  84    4.251    4.104    2.649    5.766    8.719    7.431    3.347    9.707    1.923    4.057    6.896    5.146    9.594    2.967    2.535
  85    8.538    5.460    5.830    6.276   13.235    8.762     .443    9.112    2.552    9.363    2.489   12.505   13.221    5.422    5.646
  86   10.749    3.346    3.129    2.274   18.879   14.262    2.689    3.709     .553   12.197    1.179   14.937   19.388    8.226    8.280
  87   17.744   43.073   37.650   51.355   16.102   20.755   36.393   66.370   42.649   20.834   60.140   21.373   22.492   26.734   21.353
  88    1.636    8.747    6.799   11.454    7.516    8.636    8.118   18.906    8.468    5.619   16.588    7.831   10.530    6.796    3.383
  89    2.166   10.118    7.234   12.844    5.953    3.932    4.909   20.830    7.203    4.225   14.486    6.202    8.994    3.145    2.119
  90    2.467    8.238    5.624   10.317    8.638    7.000    5.386   17.935    6.453    6.119   13.890    8.508   12.098    5.066    3.119
  91    1.883   13.060    9.853   16.221    2.619    1.694    7.026   23.772    8.712    1.317   16.151    2.164    4.652    2.066    1.677
  92   14.675   36.313   29.880   41.529    9.884    9.585   25.587   52.378   29.336   11.842   43.075   11.036   14.742   16.620   14.937
  93    6.910   19.773   15.432   24.813    8.057    5.317   11.169   36.487   15.616    7.672   24.959    8.935   11.745    5.937    6.337
  94   15.092   34.044   28.382   38.708    9.402    8.861   23.899   47.377   26.153    9.760   37.092    8.224   11.878   13.569   14.082
  95    7.842   24.549   20.837   30.973    2.705    4.915   17.029   39.778   20.738    4.186   31.667    3.317    4.668    8.458    7.013
  96    4.818   20.744   15.938   25.219    4.337    5.512   15.620   34.717   16.743    3.979   28.614    3.651    7.778    7.215    5.715
  97    7.173    5.650    4.238    5.874   11.632    8.360    3.119    8.453    1.578    6.689    4.667    7.971   12.408    5.019    4.951
  98    2.029    3.725    2.493    5.777    6.792    7.184    3.838   10.246    2.734    3.297    8.871    4.773    8.391    4.213    1.660
  99    5.944    2.818    1.416    2.652   15.297   12.041    3.882    6.944    1.193    9.465    5.209   12.168   17.420    6.103    5.298
 100    2.898    7.894    5.737   10.228    6.836    4.606    3.559   17.511    5.488    4.337   11.113    6.592    9.044    2.165    1.786

           61       62       63       64       65       66       67       68       69       70       71       72       73       74       75
```

61	0														
62	4.386	0													
63	4.441	10.841	0												
64	7.321	3.501	19.753	0											
65	15.233	9.916	31.116	1.866	0										
66	2.077	4.726	2.394	11.325	20.726	0									
67	9.906	5.735	9.947	10.598	16.078	7.956	0								
68	11.692	6.000	25.845	.579	.544	16.075	12.470	0							
69	27.023	21.250	46.528	8.233	2.430	34.472	25.600	4.977	0						
70	30.258	29.567	52.006	13.805	7.727	40.970	36.995	10.861	4.323	0					
71	13.126	6.976	25.178	2.533	2.218	15.909	9.089	1.546	5.404	12.614	0				
72	4.059	7.320	12.160	4.541	7.598	7.357	10.085	6.647	13.818	18.916	6.675	0			
73	3.587	4.630	13.697	1.814	4.933	7.173	10.700	3.660	11.853	16.461	5.009	.877	0		
74	1.460	3.505	9.431	3.315	8.484	4.272	9.560	6.019	17.223	19.902	6.801	2.297	1.179	0	
75	6.524	8.762	5.244	19.972	33.418	4.304	15.981	26.381	52.011	55.976	28.113	19.716	17.285	10.958	0
76	1.720	8.071	1.737	13.858	23.580	1.246	11.360	19.139	37.165	39.471	19.384	8.201	8.478	4.474	4.413
77	18.284	10.372	35.680	2.763	.977	24.446	17.529	1.049	3.419	9.030	2.634	11.554	7.816	10.851	35.202
78	.757	4.584	4.306	8.495	16.788	1.073	10.565	12.860	29.192	32.104	13.854	5.648	4.738	1.842	4.930
79	1.564	2.104	7.561	3.243	8.823	3.278	6.412	6.149	18.830	25.330	7.467	2.262	1.465	1.433	10.559
80	.406	4.470	6.061	6.376	13.678	2.745	11.572	10.403	25.185	26.992	12.604	4.512	3.271	1.138	6.760
81	3.406	1.308	12.043	1.422	5.931	4.974	7.840	3.376	14.926	20.888	4.560	3.514	1.348	1.229	11.950
82	2.942	1.357	11.461	1.399	6.089	4.979	8.104	3.571	15.472	21.295	5.437	3.409	1.254	1.309	11.614
83	.185	3.604	3.809	7.041	14.883	1.642	7.799	11.276	26.753	31.557	12.339	3.851	3.595	1.791	6.600
84	2.403	3.583	7.798	3.784	8.344	4.184	5.081	6.234	16.802	23.256	6.289	1.259	1.497	1.769	13.524
85	.645	4.048	6.087	7.046	15.102	2.837	11.654	11.255	27.360	28.896	13.369	6.243	4.511	1.530	5.093
86	.936	5.589	1.687	10.730	19.596	.605	8.236	15.515	32.532	37.155	15.823	5.758	6.095	3.368	5.254
87	43.477	37.480	66.580	23.307	16.396	51.084	42.243	18.940	9.940	11.142	14.532	28.067	26.363	29.607	70.124
88	10.632	7.348	20.240	6.585	9.418	11.644	10.464	7.116	14.637	19.336	3.671	8.038	6.699	5.226	20.854
89	7.149	7.672	18.886	3.815	5.839	10.312	13.778	4.824	10.607	13.750	4.056	2.860	1.964	2.444	21.709
90	7.478	8.039	17.312	6.113	9.157	9.320	12.548	7.444	14.471	18.051	5.100	4.154	3.724	3.061	20.142
91	8.865	6.715	21.309	1.352	1.714	12.264	12.221	1.403	5.984	10.807	2.044	3.150	1.570	3.700	24.511
92	29.437	28.511	47.922	13.231	6.387	37.020	31.334	10.166	2.494	4.216	10.403	14.011	13.785	19.756	57.991
93	14.004	15.532	30.488	6.798	6.039	19.715	24.115	6.929	7.833	10.619	7.504	5.114	4.427	7.713	35.412
94	25.725	23.729	41.976	10.539	5.188	32.470	27.025	8.347	4.486	9.364	11.081	12.429	11.704	18.577	51.712
95	19.669	16.000	36.285	5.081	1.271	27.132	19.653	3.084	1.266	5.083	4.531	9.431	7.839	12.332	42.250
96	17.968	14.704	32.700	5.397	2.184	22.433	17.067	3.654	2.148	8.040	2.725	6.571	6.068	10.350	40.002
97	2.013	4.877	5.690	5.788	11.175	3.309	6.539	8.837	20.945	25.829	9.744	2.624	2.832	2.410	11.316
98	4.218	3.493	10.056	3.888	7.927	5.714	3.887	5.528	15.247	[illegible]	3.804	3.349	3.065	1.946	13.985
99	2.588	5.641	6.260	8.812	15.741	2.136	8.300	12.388	25.629	31.199	10.527	3.635	4.239	2.326	10.264
100	5.212	5.249	15.831	3.518	7.123	7.457	12.387	5.232	13.852	18.056	4.892	3.004	1.681	1.581	16.987

	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
76	0														
77	27.843	0													
78	.927	20.196	0												
79	4.943	11.582	2.571	0											
80	2.081	16.799	.597	1.841	0										
81	7.336	7.674	3.454	1.124	2.857	0									
82	7.094	7.990	3.379	.725	2.415	.145	0								
83	1.942	17.903	1.061	1.042	.872	3.143	2.663	0							
84	5.532	11.517	3.624	.511	2.958	1.982	1.727	1.724	0						
85	2.139	17.457	.678	2.572	.252	3.236	2.881	1.176	4.013	0					
86	.530	23.607	.817	2.624	1.624	5.161	4.812	.708	3.105	1.951	0				
87	53.334	15.306	44.234	37.193	41.838	29.575	32.166	44.260	33.931	43.017	50.246	0			
88	13.869	9.744	9.712	8.703	10.413	5.236	6.894	10.620	7.799	10.213	12.449	15.926	0		
89	11.550	8.204	7.147	5.377	6.511	3.232	4.123	7.600	4.767	7.501	9.896	16.759	2.720	0	
90	10.631	11.280	6.938	6.489	7.304	4.279	5.562	7.846	5.608	7.901	9.425	17.652	1.401	.617	0
91	14.456	4.135	9.278	4.602	7.688	2.522	2.926	8.742	4.089	9.119	11.643	18.285	5.369	1.757	3.823
92	37.928	10.210	31.148	22.093	27.214	19.295	19.745	29.575	18.981	30.566	34.076	13.088	19.322	12.194	16.434
93	21.137	9.272	15.071	10.812	13.015	8.472	9.161	14.759	9.946	15.152	18.526	14.318	9.053	2.446	4.775
94	34.481	9.578	28.078	17.321	23.686	16.312	15.766	25.143	15.346	27.256	29.608	25.349	23.563	14.640	20.112
95	28.789	2.764	22.354	12.784	18.185	10.748	10.632	19.315	11.123	20.212	24.505	16.043	13.859	9.071	13.052
96	25.246	4.781	19.153	11.361	16.968	8.849	9.569	17.497	9.234	19.253	21.293	12.020	8.691	4.865	7.332
97	3.638	15.319	2.643	1.022	2.082	3.087	2.540	1.512	.755	3.208	1.945	41.007	10.975	7.072	8.127
98	6.859	9.616	4.692	2.519	4.519	2.315	2.743	3.683	1.561	4.804	5.038	26.634	3.366	3.736	3.465
99	3.252	19.162	2.075	3.297	3.438	3.948	4.564	2.468	3.022	3.915	2.372	35.313	5.713	4.426	3.198

```
100    9.206    9.234    4.985    3.896    4.775    1.946    2.751    5.563    4.020    5.411    7.617  21.19[illegible]    2.760     .452     .800

         91       92       93       94       95       96       97       98       99      100
 91       0
 92   8.031        0
 93   3.366    7.562        0
 94   7.520    2.979   10.400        0
 95   4.125    3.572    7.774    3.017        0
 96   2.174    3.082    3.864    4.617    2.370        0
 97   6.014   21.791   13.081   16.975   14.000   12.595        0
 98   4.064   18.793   10.709   18.192   10.873    8.629    2.965        0
 99   7.840   27.277   11.360   26.876   20.796   14.749    3.091    3.217        0
100   2.445   18.529    3.997   17.701   11.621    7.204    6.119    3.395    2.960        0
```

APPENDIX F

LISTING OF THE MCKEON CLUSTER ANALYSIS PROGRAM

```
      PROGRAM MCKEON
C
C  THIS PROGRAM OBTAINED FROM NATIONAL INSTITUTES OF HEALTH
C     COMPUTER CENTER IN BETHESDA, MARYLAND.  MODIFIED TO RUN
C     UNDER OS3, AND CERTAIN CONVENIENCE CHANGES MADE
C     JUNE 1974 BY K. BYRAM, US ENVIRONMENTAL PROTECTION AGENCY
C
C     MCKEON CLUSTER ANALYSIS     VERSION  I
      DIMENSION B(150, 150), LV(150, 150),
     1  KV(150), KC(150), C(150), FMT(180)
     2 ,R(150),H(150),IOUT(150)
      INTEGER C,FMT,HARDWARE
      REAL1 B
      EQUIVALENCE (B,LV),(R,C),(H,KV),(FMT,IOUT)
C
C  PROGRAM READS UNIT 60
C         WRITE UNIT 61
C
      DO  1 LUN=1,63
      IF(.NOT.HARDWARE(LUN))GO TO 3
    1 CONTINUE
      STOP 1
    3 CALL EQUIP(LUN,SHFILE )
C*****************************************************************
C                      INPUT FROM USER
C*****************************************************************
C....SPECIFICATIONS INPUT
    2 READ(60,2020)N,KOP,NV,KRIT1,KRIT2,MMCOL,MATOP
      IF(EOF(60))GO TO 216
 2020 FORMAT (10I4)
      IF(N.LE.0)STOP
      NNCOL=20*MMCOL
      READ(60,1199) (FMT(II),II=1,NNCOL)
 1199 FORMAT (20A4)
      WRITE(61,1198)N,KOP,NV,KRIT1,KRIT2,MMCOL,MATOP
      MATOP=1+MATOP
 1198 FORMAT( 1MCKEON CLUSTER ANALYSIS VERSION I.1 /
     *    0CONTROL INPUT: ,10I4)
      WRITE(61,1197)(FMT(II),II=1,NNCOL)
 1197 FORMAT(14X,1H:,20A4)
      WRITE(61,1196)
 1196 FORMAT( 0FIRST ROW OF DATA FOR VERIFICATION- )
      NM1=N-1
      FN=N
      GO TO (5,18,7,7),KOP
C
C....KOP=1     INPUT DATA AS CORRELATION MATRIX IN UPPER
C....          TRIANGULAR FORM, MINUS DIAGONALS
C
    5 DO 6 I=1,NM1
      B(I,I)=1.
      IP1=I+1
      READ(60,FMT) (B(I,J),J=IP1,N)
      IF(I.EQ.1)WRITE(61,1195)(B(1,J),J=IP1,N)
 1195 FORMAT(10E12.3)
    6 CONTINUE
```

```
      B(N,N)=1.
      IF(NV.NE.1)GO TO 25
C
C  REFLECTION IF REQUESTED
C
      WRITE(61,802)
  802 FORMAT(1H  ,19HVARIABLES REFLECTED//)
      DO 804 I=1,N
      DO 804 J=I,N
  804 B(J,I)=B(I,J)
      WRITE(LUN) ((B(I,J),J=1,N),I=1,N)
      REWIND 2
      DO 856 J=1,N
      B(J,J)=0.
      KC(J)=1.
      BM=0.
      DO 854 I=1,N
      TEMP=ABS (B(I,J))
      IF(TEMP.LE.BM)GO TO 854
      BM=TEMP
      H(J)=B(I,J)
      IM=I
  854 B(I,J)=0.
  856 B(IM,J)=H(J)
      DO 810 I=1,N
      R(I)=0.
      DO 810 J=1,N
  810 R(I)=R(I)+B(I,J)
      ITR=0
  811 RM=FN
      DO 816 I=1,N
      TEMP=R(I)+H(I)
      IF(TEMP.GE.RM)GO TO 816
      RM=TEMP
      IM=I
  816 CONTINUE
      IF(RM.GE.0.)GO TO 890
      DO 822 J=1,N
      B(IM,J)=-B(IM,J)
  822 B(J,IM)=-B(J,IM)
      DO 824 J=1,N
      H(J)=H(J)+2.*B(IM,J)
  824 R(J)=R(J)+2.*B(J,IM)
      H(IM)=-H(IM)
      R(IM)=-R(IM)
      KC(IM)=-KC(IM)
      WRITE(61,830) IM
  830 FORMAT (1H ,6X,I8)
      ITR=ITR+1
      IF(ITR.LT.N)GO TO 811
  890 CONTINUE
      READ(LUN)      ((B(I,J),J=1,N),I=1,N)
      REWIND 2
      DO 870 I=1,N
      IF(KC(I).GE.0)GO TO 870
      DO 864 J=1,N
      B(I,J)=-B(I,J)
  864 B(J,I)=-B(J,I)
  870 CONTINUE
      GO TO 25
C
C....KOP=2...INPUT DATA AS COVARIANCE MATRIX IN FULL MATRIX FORM
```

```
C
   18 DO 20 I=1,N
      READ(60,FMT) (B(I,J),J=I,N)
      IF(I.EQ.1)WRITE(61,1195)(B(I,J),J=1,NV)
   20 CONTINUE
      GO TO 25
C
C....KOP=3 OR 4...INPUT DATA AS RAW NUMBERS
C
    7 DO 8 I=1,N
      READ(60,FMT) (B(I,J),J=1,NV)
      IF(I.EQ.1)WRITE(61,1195)(B(I,J),J=1,NV)
    8 CONTINUE
      IF(KOP.EQ.4)GO TO 602
C...KOP=3...STANDARDIZE OVER COLUMNS
      DO 10 J=1,NV
      SUM=0.
      SS=0.
      DO 9 I=1,N
      SUM=SUM+B(I,J)
    9 SS=SS+B(I,J)**2
      FMEAN=SUM/FN
      FMSQ=SS/FN
      SD=SQRT (FMSQ-FMEAN**2)
      DO 10 I=1,N
   10 B(I,J)=(B(I,J)-FMEAN)/SD
C....COMPUTE DISTANCES....USING
  602 IF(N.GT.75)GO TO 14
C.........TOP OF MATRIX SINCE N LT 75
      DO 12 I=1,N
      DO 12 J=I,N
      B(I+75,J)=0.
      DO 12 K=1,NV
   12 B(I+75,J)=B(I+75,J)+B(I,K)*B(J,K)
      DO 13 I=1,N
      DO 13 J=I,N
   13 B(I,J)=B(I+75,J)
      GO TO 25
C.........USING EXTERNAL SCRATCH FILE SINCE N GT 75
   14 DO 15 J=1,NV
   15 WRITE(LUN)      (B(I,J), I=1,N)
      REWIND 2
      DO 16 I=1,N
      DO 16 J=I,N
   16 B(I,J)=0.
      DO 17 K=1,NV
      READ(LUN)     (R(I),I=1,N)
      DO 17 I=1,N
      DO 17 J=I,N
   17 B(I,J)=B(I,J)+R(I)*R(J)
C*****************************************************************
C                INPUT COMPLETE...INITIALIZE
C*****************************************************************
   25 TB=0.
      DO 26 I=1,NM1
      IP1=I+1
      DO 26 J=IP1,N
      B(I,J)=B(I,I)+B(J,J)-2.*B(I,J)
   26 TB=TB+B(I,J)
      DO 27 I=1,N
   27 B(I,I)=0.
      DO 28 I=1,NM1
      IP1=I+1
      DO 28 J=IP1,N
   28 B(J,I)=B(I,J)
      NRC=N
      KSH=0
      LOC=1
      IF(KRIT1.EQ.N.AND.MATOP.EQ.1)GO TO 1021
      WRITE(61,2000)
 2000 FORMAT( -SQUARED DISTANCES BETWEEN POINTS BEFORE CLUSTERING )
      GO TO 1000
 1021 CONTINUE
      IF(MATOP.EQ.3)WRITE(61,2014)
      NC=N
      NCM1=NC-1
      BMIN=0.
      TEMP=SQRT (FN)
      IF(KRIT1.LE.0)KRIT1=2.*TEMP+.5
      IF(KRIT2.LE.0)KRIT2=2
      MCL=0
      MIS=N
      DO 120 I=1,N
      C(I)=1
      KV(I)=I
  120 KC(I)=I
C*****************************************************************
C        MAIN LOOP
C*****************************************************************
C...FIND MINIMUM ENTRY IN OFF DIAGONAL ELEMENTS
  130 BPR=BMIN
      BMIN=1.E30
      DO 134 I=1,NCM1
      IP1=I+1
      DO 134 J=IP1,NC
      IF(B(I,J).GE.BMIN)GO TO 134
      BMIN =B(I,J)
      IM=I
      JM=J
  134 CONTINUE
      DEL=BMIN-BPR
      IF(NC.GT.KRIT1)GO TO 139
      GO TO (149,1022,135),MATOP
  135 WRITE(61,420) BMIN,IM,JM,DEL,MIS,MCL
  420 FORMAT (1H ,8X,F8.3,9X,I3,1H,,I3,8X,F10.3,18X,I8,15X,I10)
  139 CN=C(IM)+C(JM)
      DO 136 K=1,NC
      B(IM,K)=AMAX1(B(IM,K),B(JM,K))
  136 B(K,IM)=B(IM,K)
      IF(JM.GE.NC)GO TO 141
C...CLOSE UP MATRIX NOW THAT WE ELIMINATED A CLUSTER
      DO 138 I=1,NC
      DO 138 J=JM,NCM1
  138 B(I,J)=B(I,J+1)
      DO 140 J=1,NCM1
      DO 140 I=JM,NCM1
  140 B(I,J)=B(I+1,J)
C...ADJUST KC TO SHOW NEW ARRANGEMENT
  141 DO 146 I=1,N
      IF(KV(I).EQ.KC(JM))KV(I)=KC(IM)
  146 CONTINUE
      KTR=1
```

```
C...ADJUST NUMBER OF ISOLATED POINTS
      IF(C(IM).LE.1)KTR=KTR+1
      IF(C(JM).LE.1)KTR=KTR+1
      GO TO (311,314,313), KTR
  311 MCL=MCL-1
      GO TO 314
  313 MCL=MCL+1
  314 MIS=NCM1-MCL
      IF(JM.GE.NC)GO TO 321
C...CLOSE UP COUNTER ARRAYS
      DO 148 J=JM,NCM1
      C(J)=C(J+1)
  148 KC(J)=KC(J+1)
  321 C(IM)=CN
      NC=NCM1
      NCM1=NC-1
      GO TO 130
C******************************************************************
C     OUTPUT SECTION
C:*****************************************************************
  149 WRITE(61,2006)
 2006 FORMAT(1H1 ,44HMAXIMUM SQUARED DISTANCE BETWEEN CLUSTERS    ,
     1 53HMAXIMUM SQUARED DISTANCE WITHIN CLUSTERS IN DIAGONALS)
      NRC=NC
      KSH=75
      LOC= 2
C      LOWER TRIANGULAR MATRIX PRINTOUT
 1000 DO 1002 JL=1,NRC,15
      JU=JL+14
      IF(JU.GT.NRC)JU=NRC
      WRITE(61,1010)(J,J=JL,JU)
 1010 FORMAT(1H0,2X,15I8)
      DO 1014 I=JL,NRC
      JUU=JU
      IF(JUU.GT.I)JUU=I
 1014 WRITE(61,1016)I,(B(I,J),J=JL,JUU)
 1002 CONTINUE
 1016 FORMAT(1H ,I4, 15F8.3)
      GO TO (1021,1022), LOC
 1022 CONTINUE
      WRITE(61,2008)
 2008 FORMAT(1H-,22X, PTS INCLUDED IN CLUSTER ,
     *     (ORIGINAL NUMBERING OF DATA) )
      DO 156 I=1,NC
      K=0
      DO 152 J=1,N
      IF(KV(J).NE.KC(I))GO TO 152
      K=K+1
      IOUT(K)=J
  152 CONTINUE
  156 WRITE(61,160)I,C(I),(IOUT(J),J=1,K)
  160 FORMAT(  CLUSTER ,I4,1H*,I4, PTS ,20I5/(21X,20I5/))
      WRITE(61,2014)
 2014 FORMAT(1H0 ,7X, 22HNEXT CLUSTER.  MAXIMUM ,11X,
     1 17HCHANGE IN MAXIMUM ,11X ,9HNUMBER OF
     2 14X,17HCLUSTERS WITH TWO/1H ,7X,26HSQUARED DISTANCE, LOCATION,
     3 16HSQUARED DISTANCE,12X ,15HISOLATED POINTS,8X,
     4 14HOR MORE POINTS//)
      IF(NC.GT.KRIT2)GO TO 135
      WRITE(61,420)              BMIN, IM, JM, DEL,MIS,MCL
C....RETURN TO GET ANOTHER CASE OR EXIT
      GO TO 2
  216 CALL UNEQUIP(LUN)
      END
```